Principles of Micro- and Nanofabrication for Electronic and Photonic Devices

Materials: Structures and Synthesis

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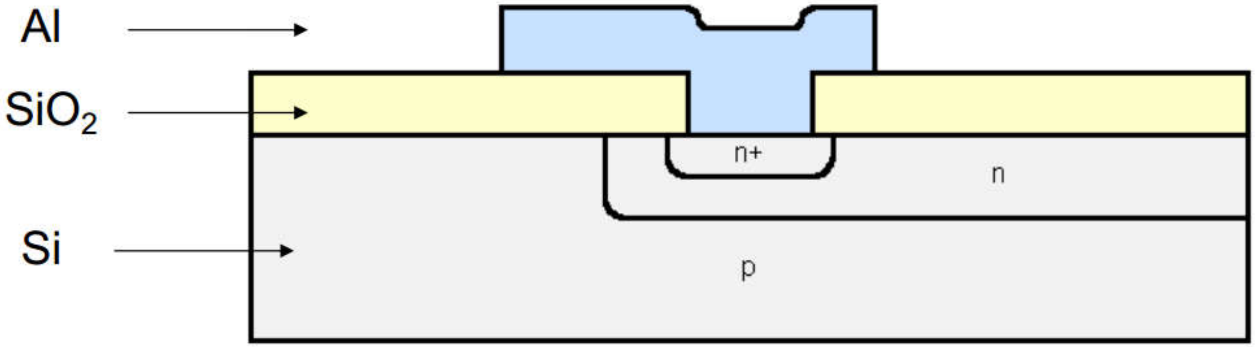
Raw Materials

MOS: Metal-Oxide-Semiconductor



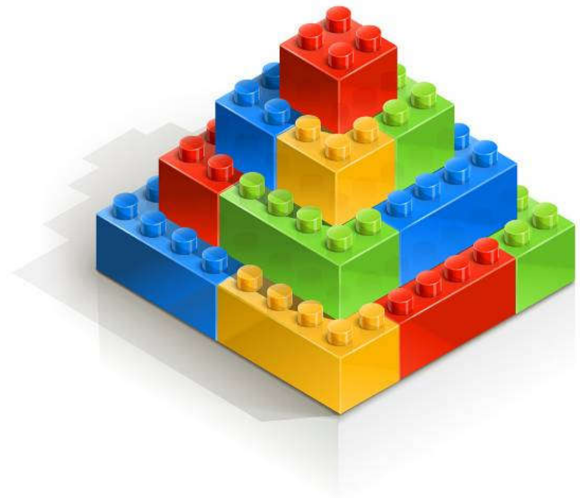
Silicon

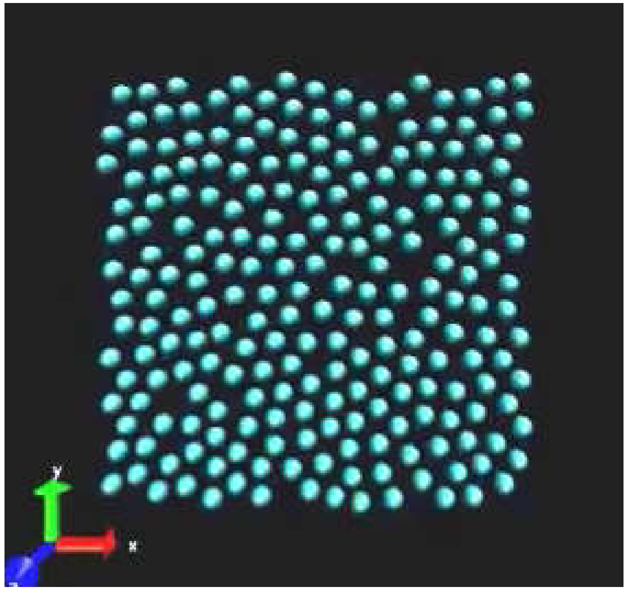
SiO_2

Metal

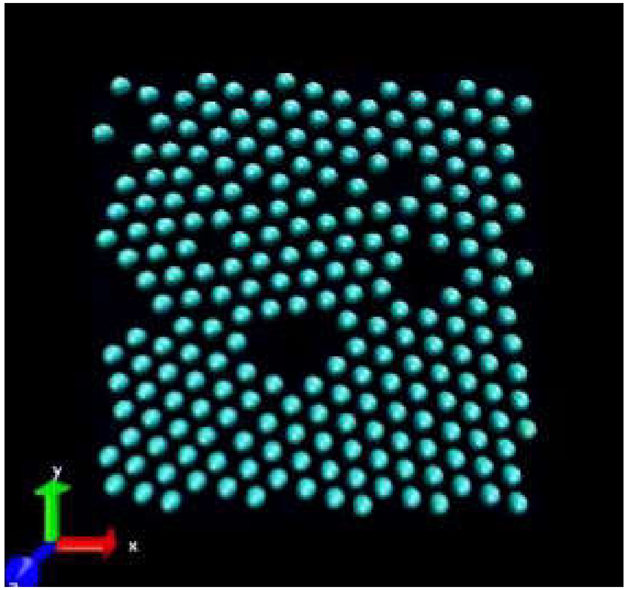
Crystal Structures

?





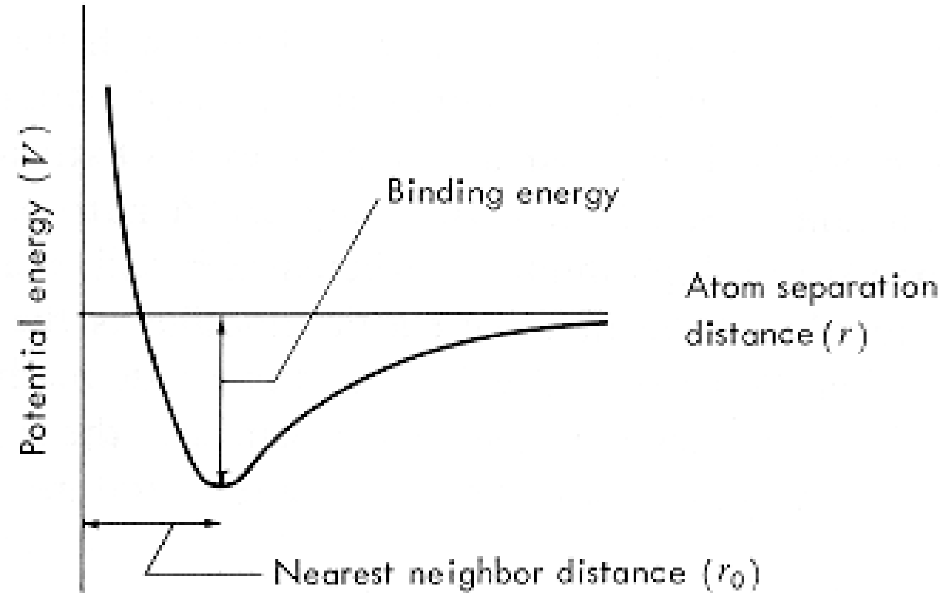
Video

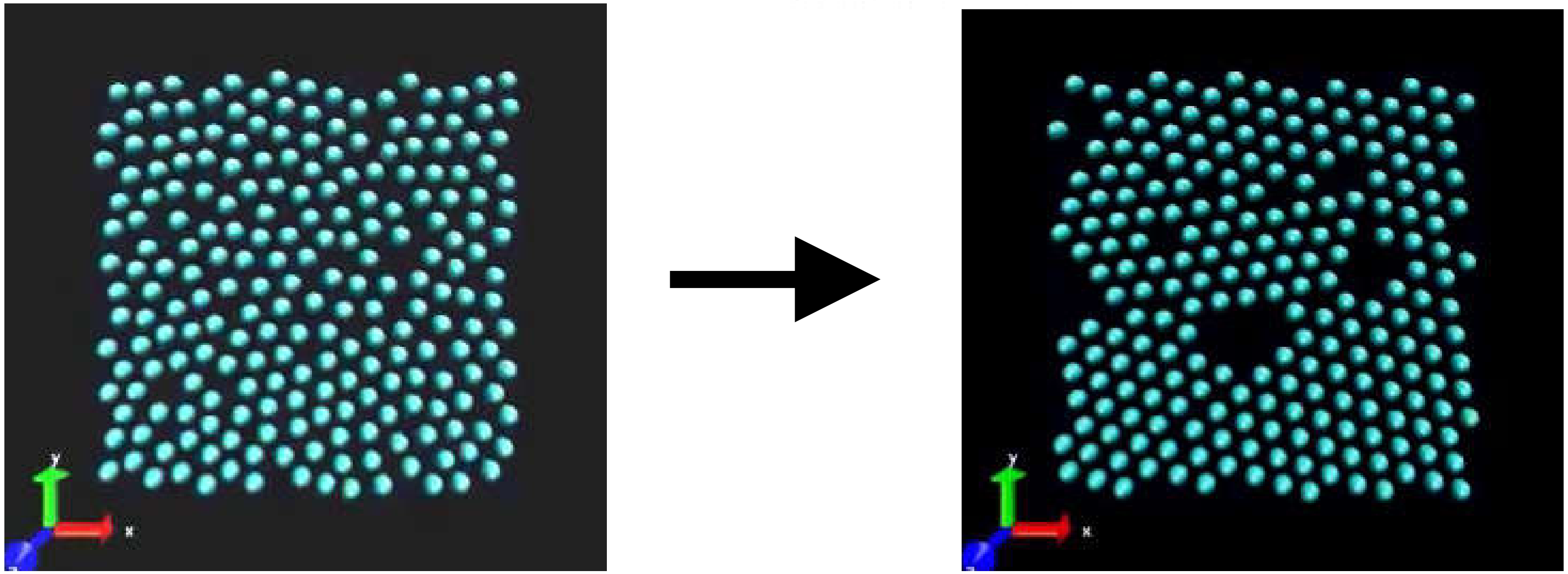


It is all about *energy*

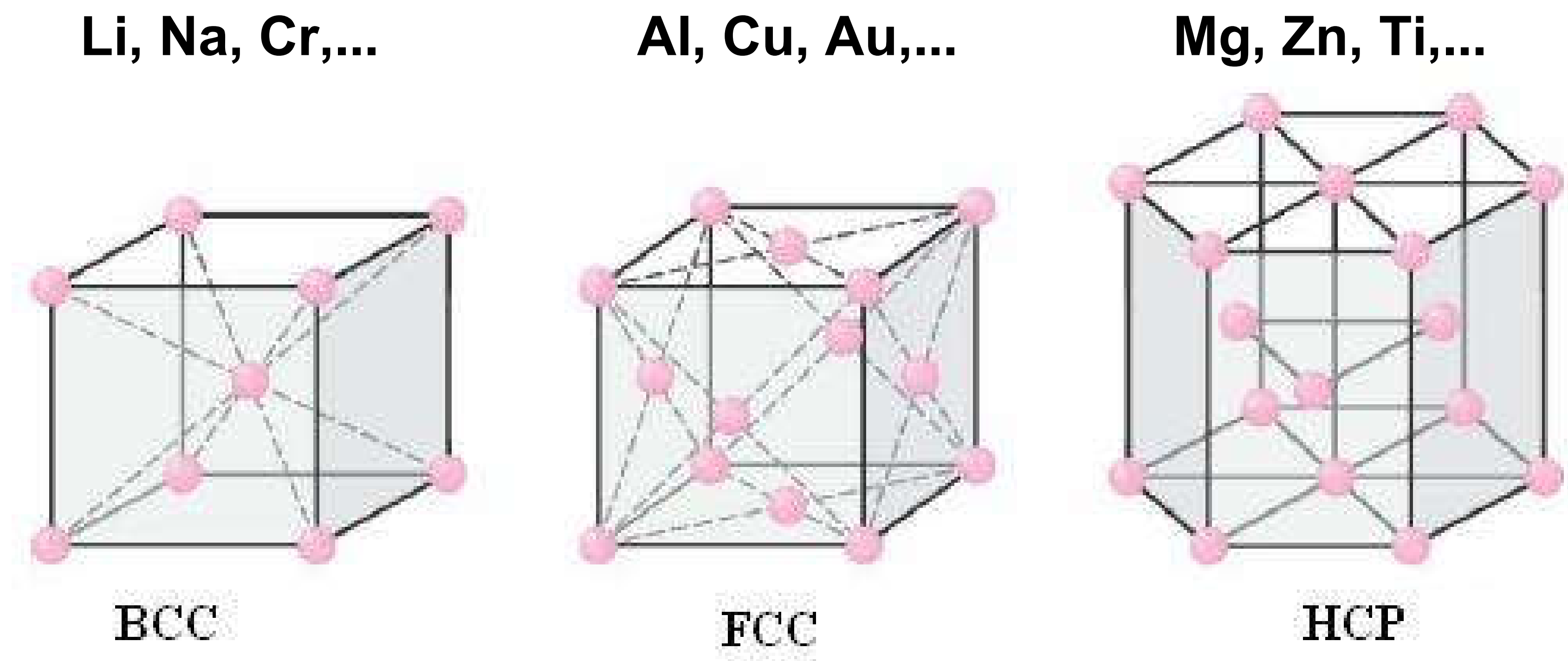
Lennard-Jones Potential

$$V(r) = \frac{A}{r^{12}} - \frac{B}{r^{6}}$$





Crystal Structures



- **3D:**
  - **14 Bravais lattices**
  - **32 point groups**
  - **230 space groups**

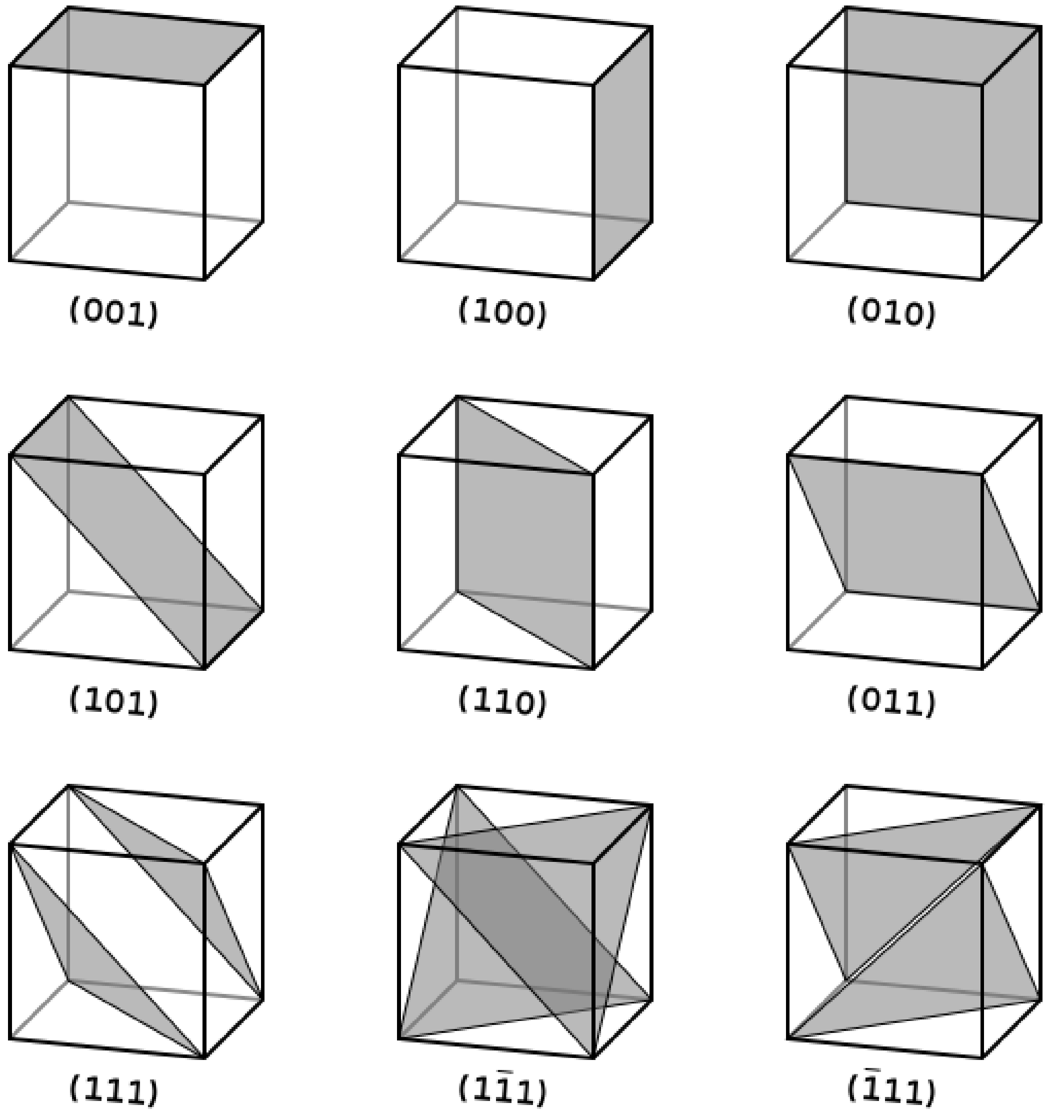
https://en.wikipedia.org/wiki/Crystal_structure

Miller Indices

(*lmn*) plane

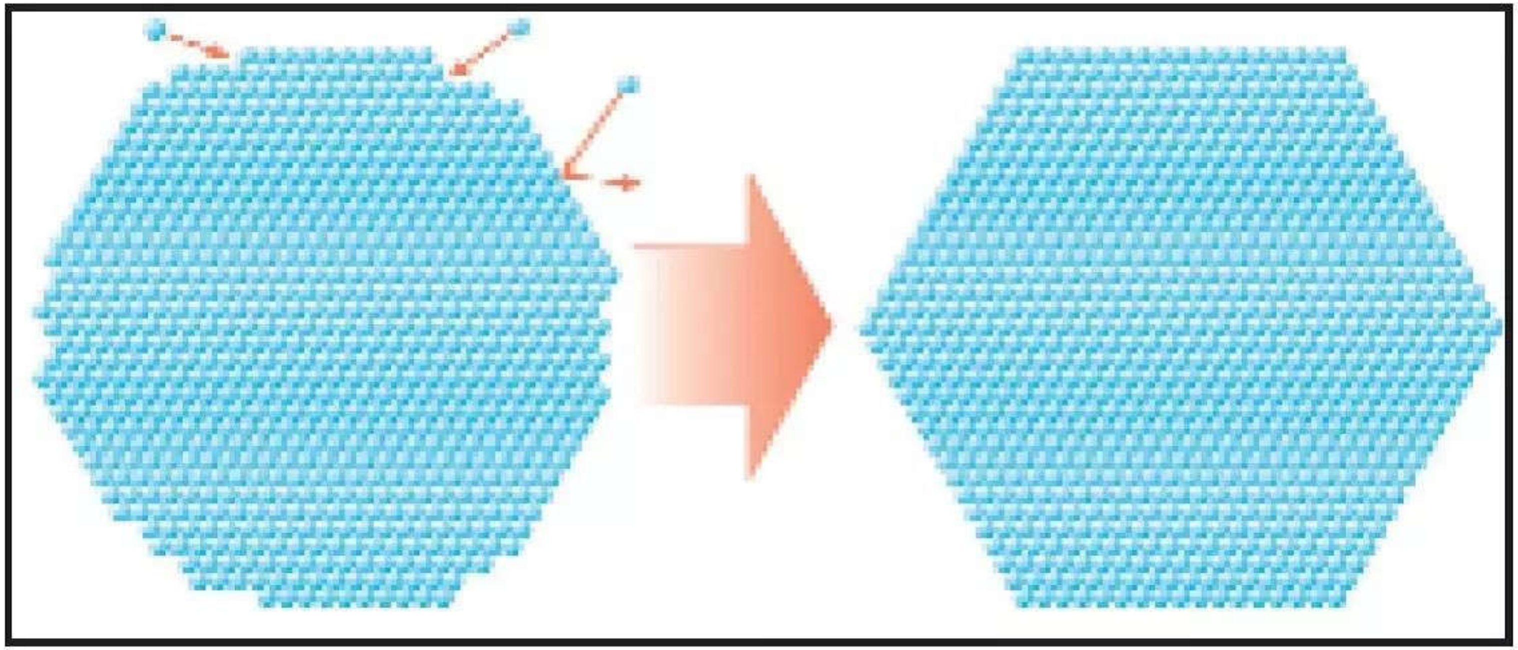
intercepts at

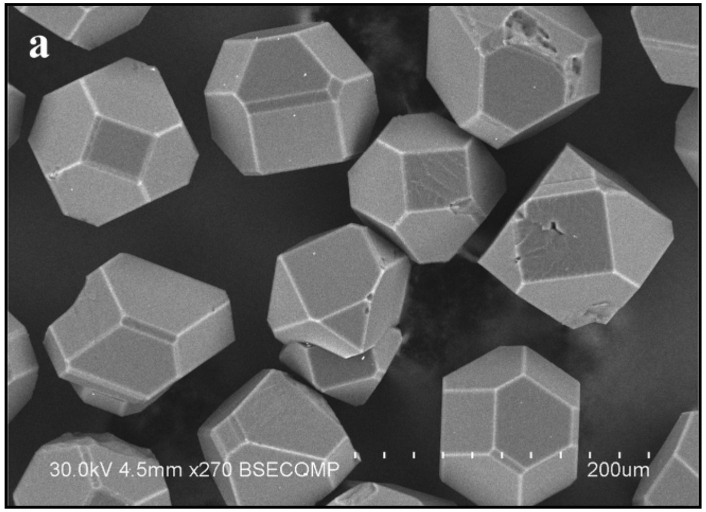
a_1/l, a_2/m, a_3/n



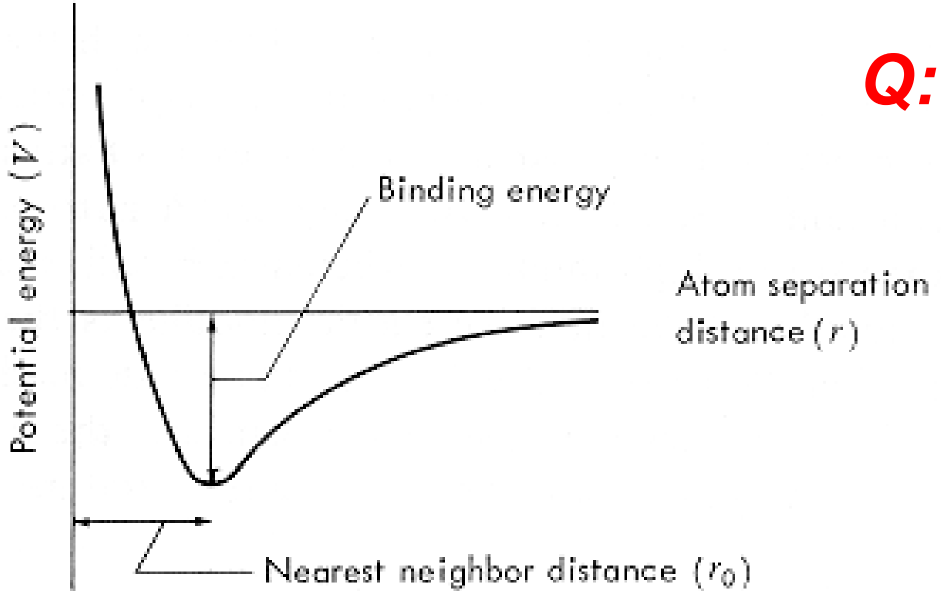
https://en.wikipedia.org/wiki/Crystal_structure

Crystals

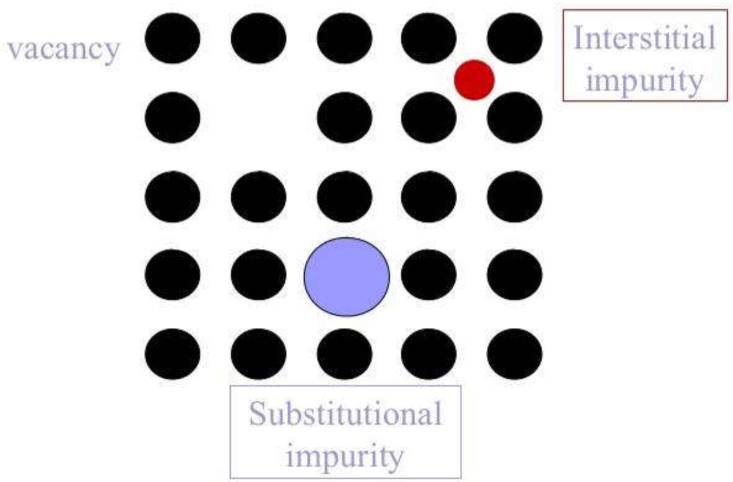




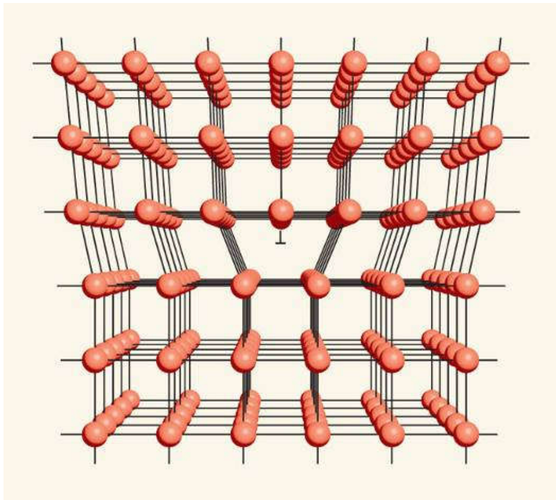
Defects in Crystals



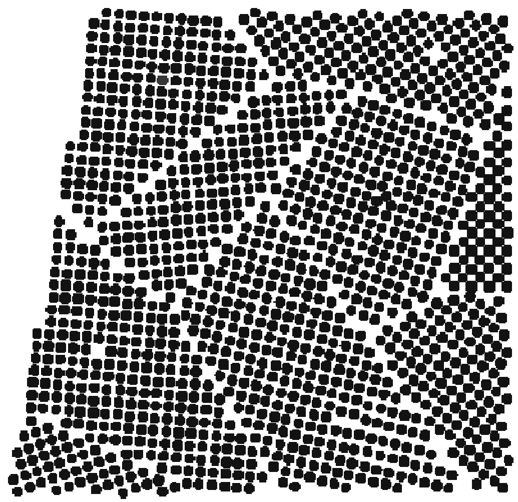
Q: why?



0D
point defect

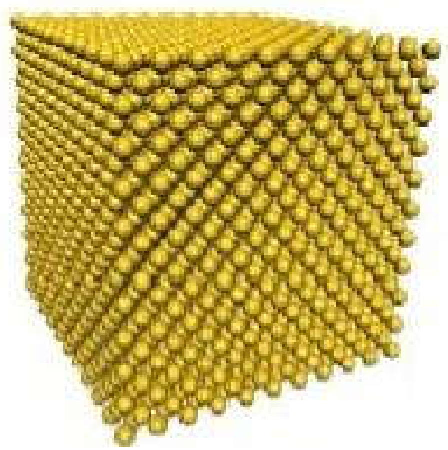


1D
dislocation



2D
grain boundary

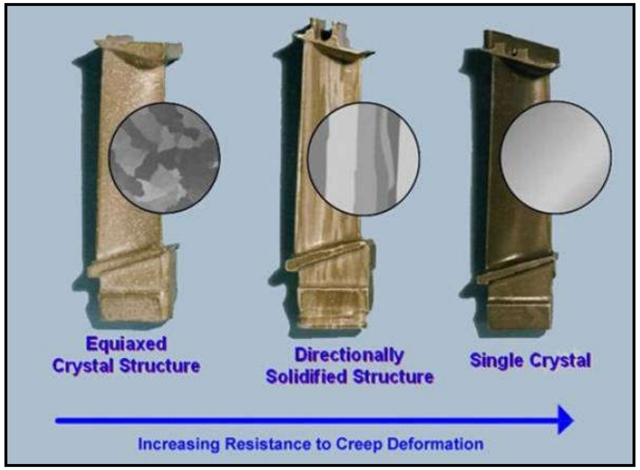
Single Crystal (Mono Crystal)



Quartz

Sugar

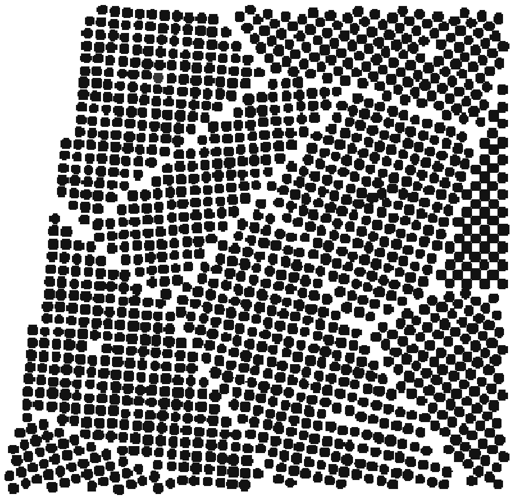
Silicon wafers,
GaAs, GaN, sapphire, ...



turbine blade

Polycrystal

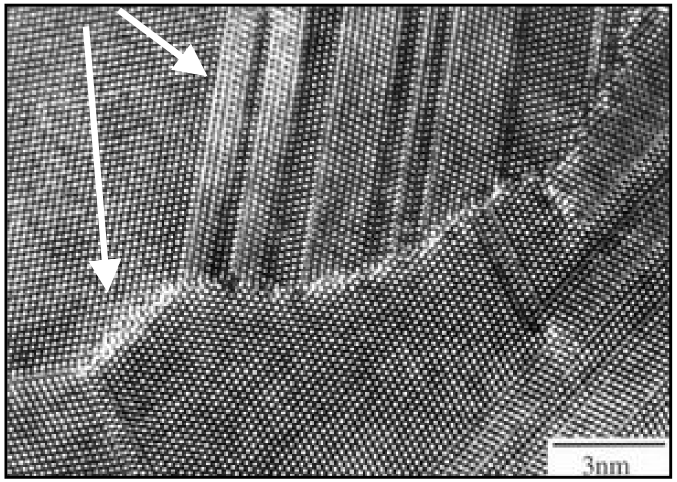
Q: why blue?



grain boundary

Poly-Crystalline Solar Cell

Mono-Crystalline Solar Cell



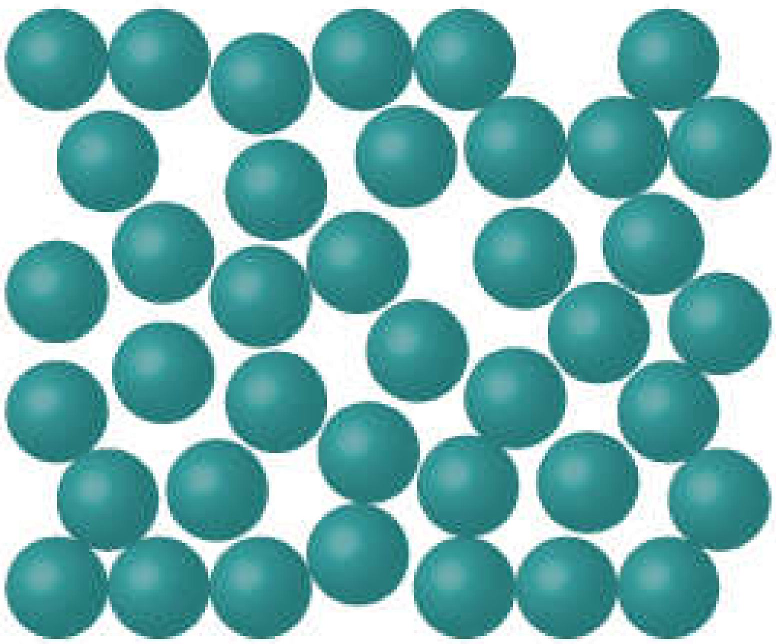
polycrystalline silicon

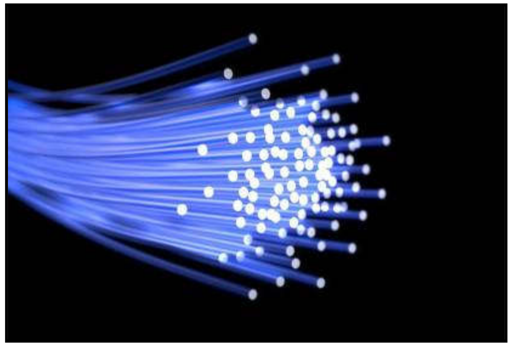
metals

ceramics

Amorphous Materials

- **Defects are everywhere ...**





silica fiber

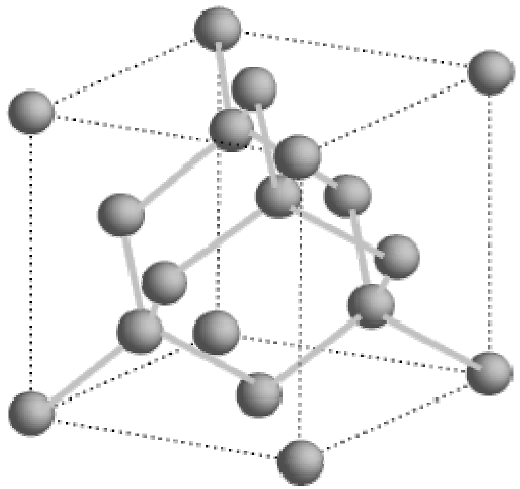
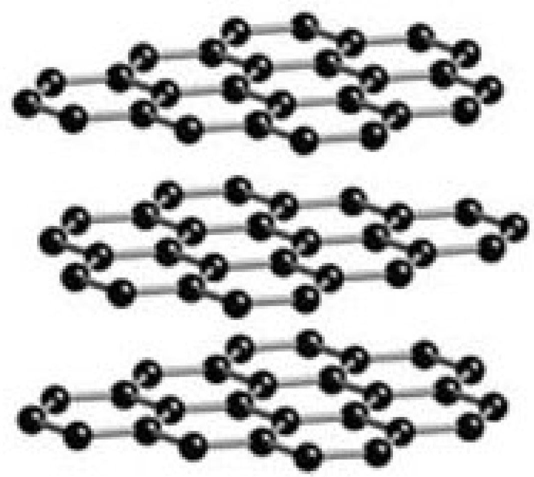
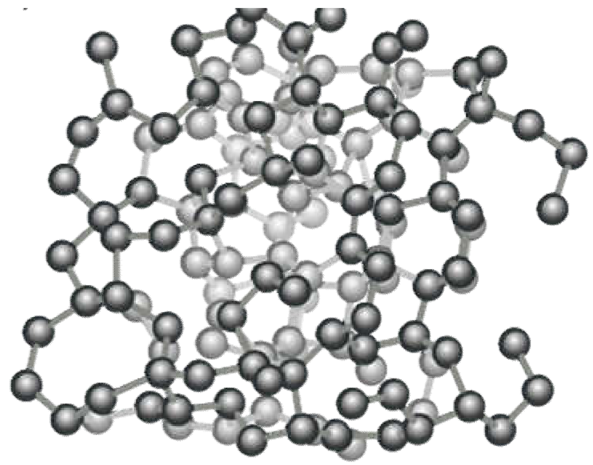
glass

plastics

Q: why is glass transparent?

Carbon



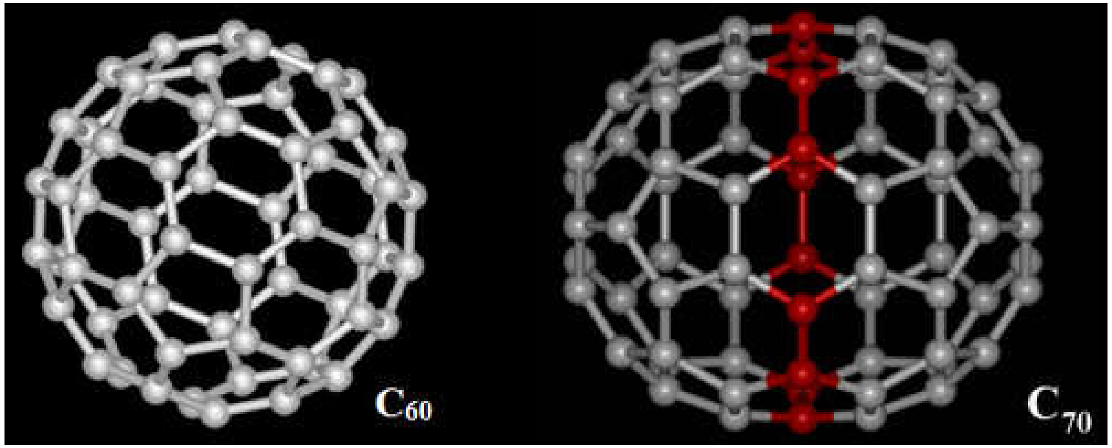
diamond

graphite

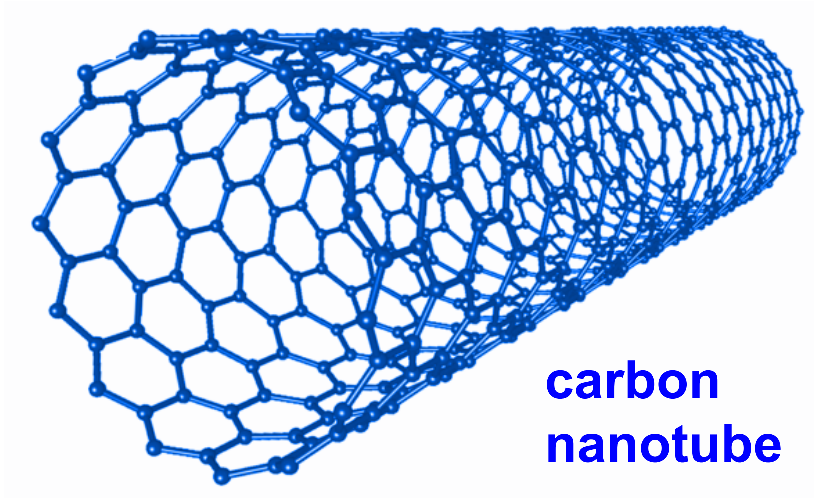
amorphous carbon

Q: which one is electrically conductive, diamond or graphite?

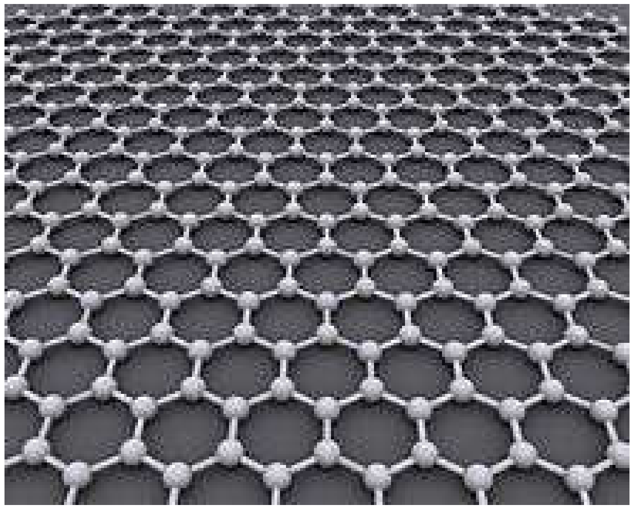
Carbon



H. Kroto, R. Curl, R. Smalley
1996 Nobel Prize in Chemistry



S. Iijima, *Nature* **354,** 56 (1991)

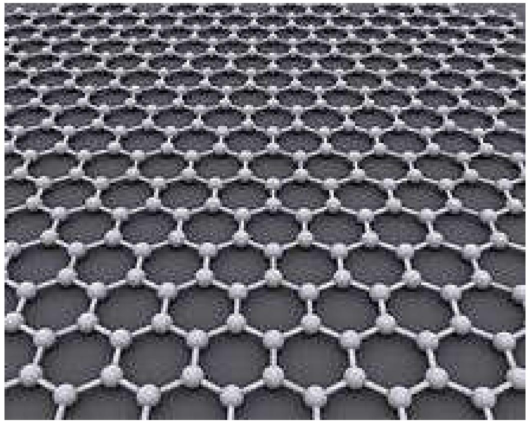


graphene

A. Geim, K. Novoselov
2010 Nobel Prize in Physics

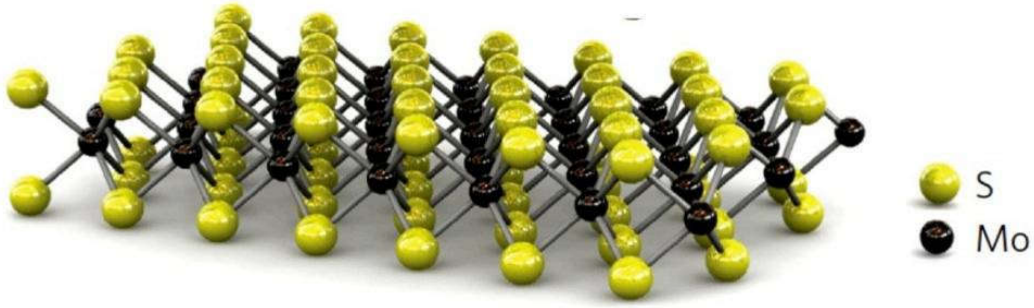
2D Materials

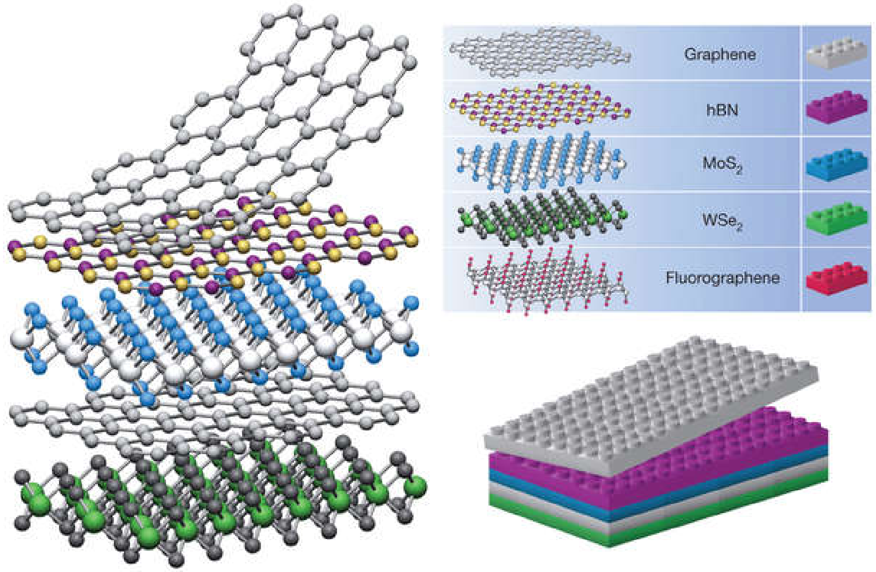
- Single atomic layer crystal



graphene

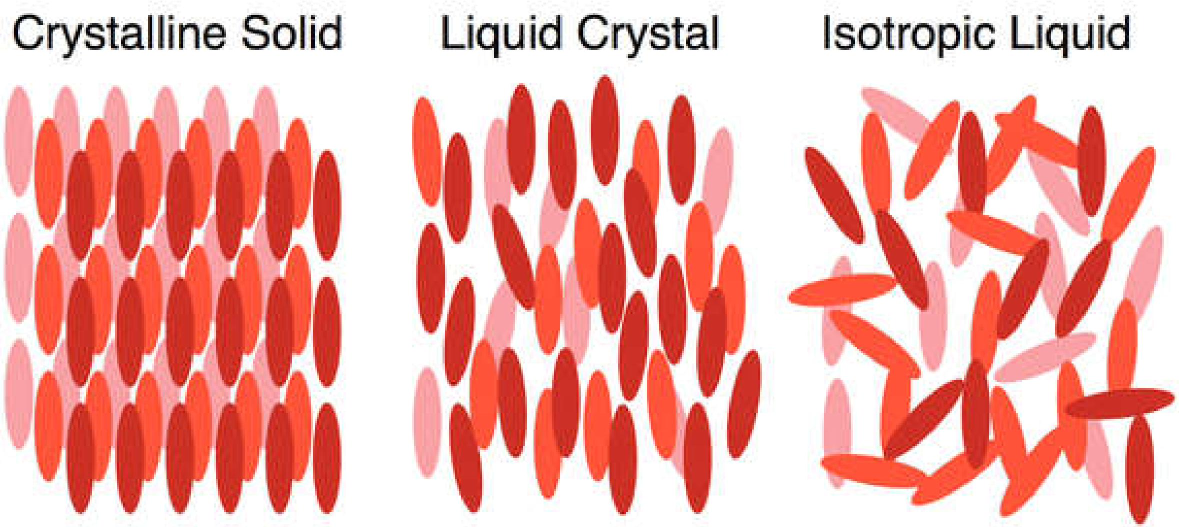
A. Geim, K. Novoselov
2010 Nobel Prize in Physics





Transition metal dichalcogenide (TMDC)
MoS_2, WSe_2, ...

Liquid Crystals



Liquid crystal display (LCD)

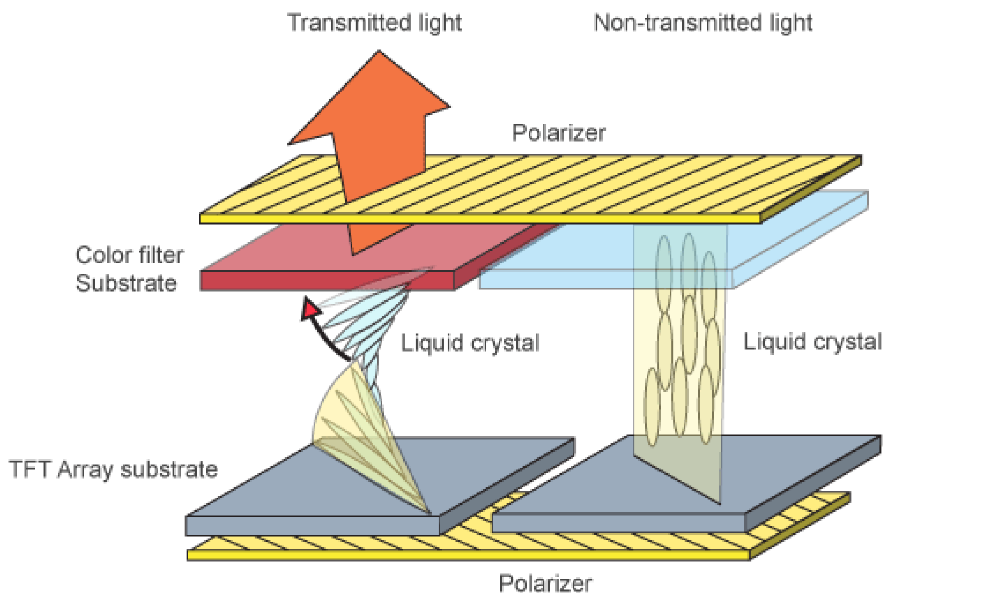
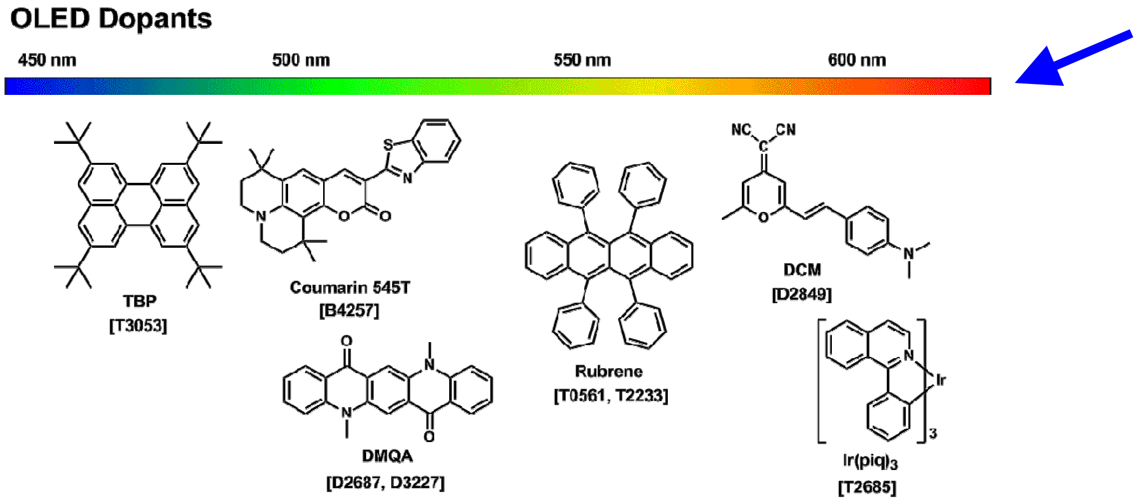


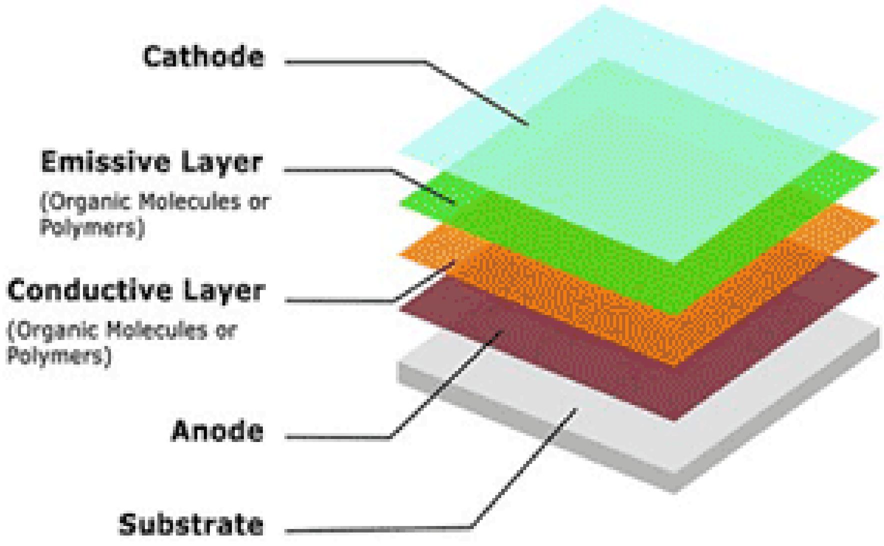
Diagram 2: The Fundamental Photonics of Liquid Crystal (Twisted Nematics)

P. de Gennes
1991 Nobel Prize in Physics

Organic Materials

- **Small Molecules**

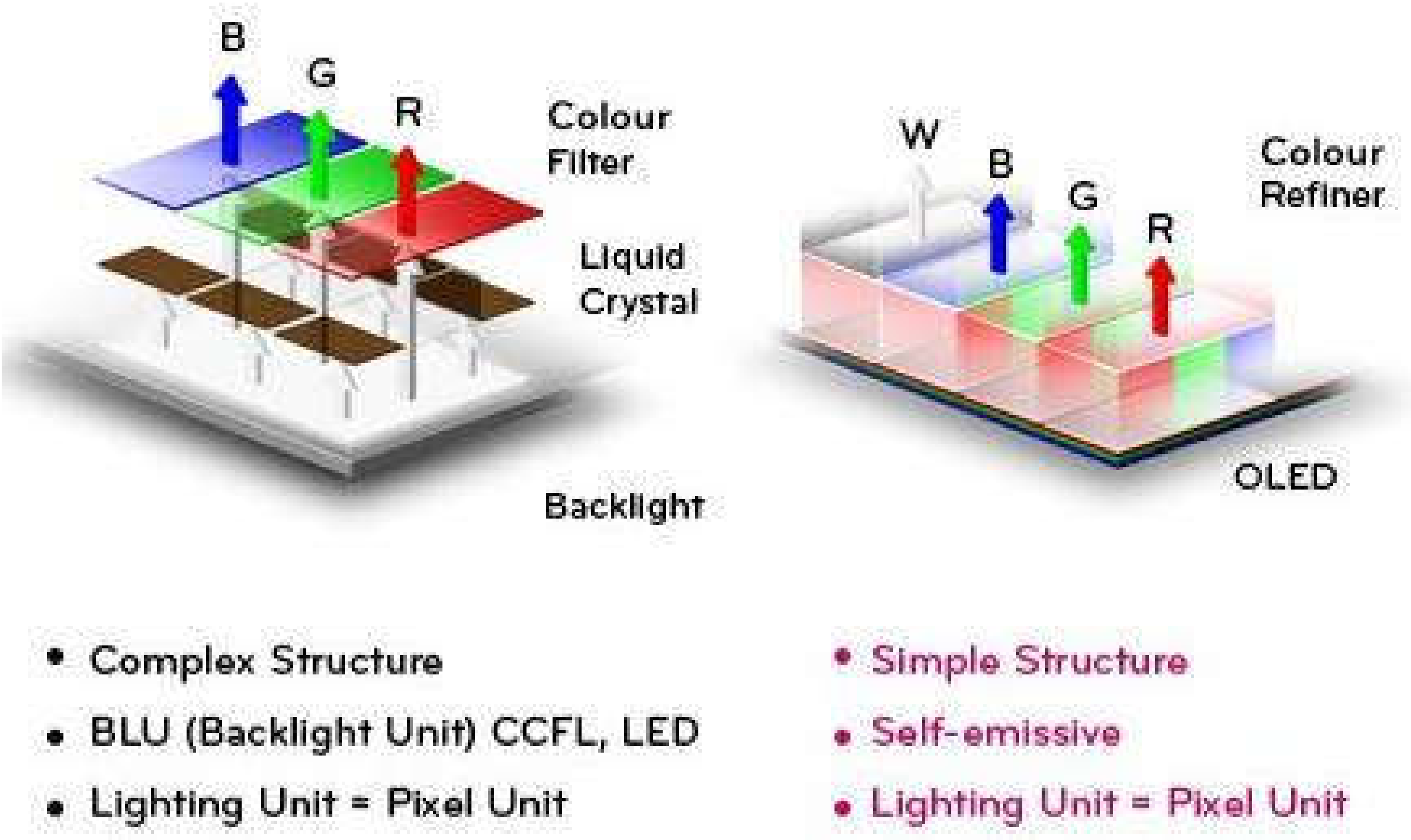




OLED

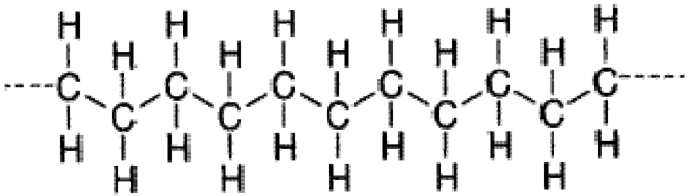
Organic Materials

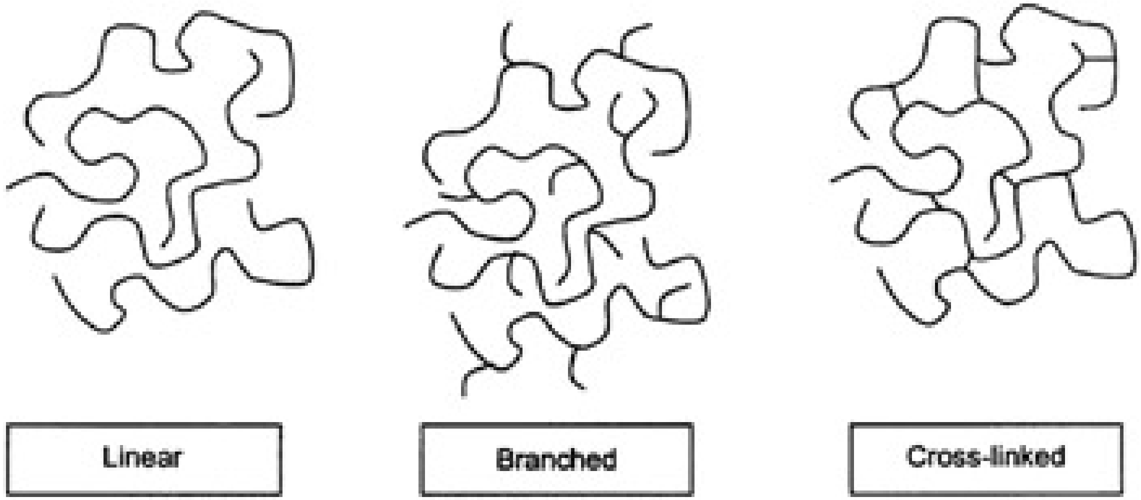
LCD vs. OLED

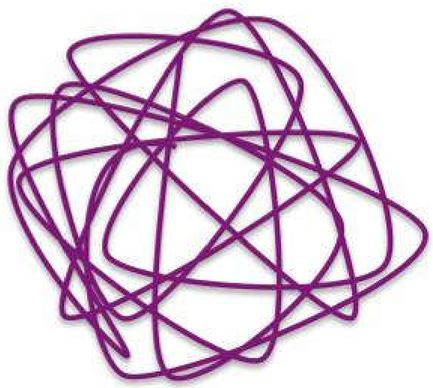


Organic Materials

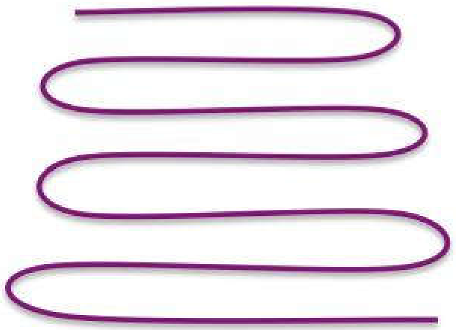
- **Polymers**



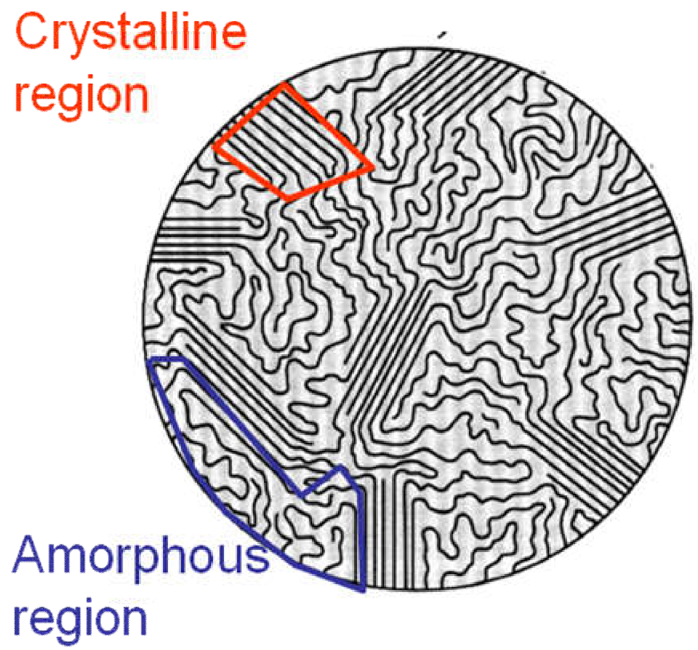




Amorphous

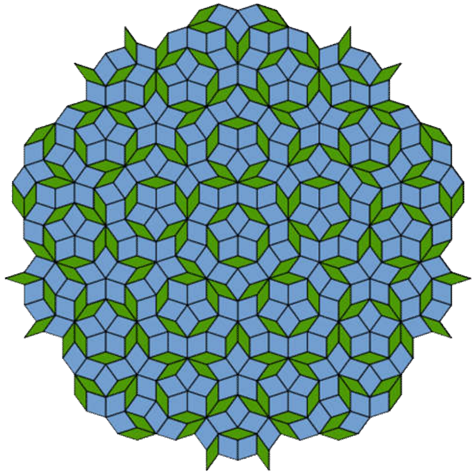


Crystalline

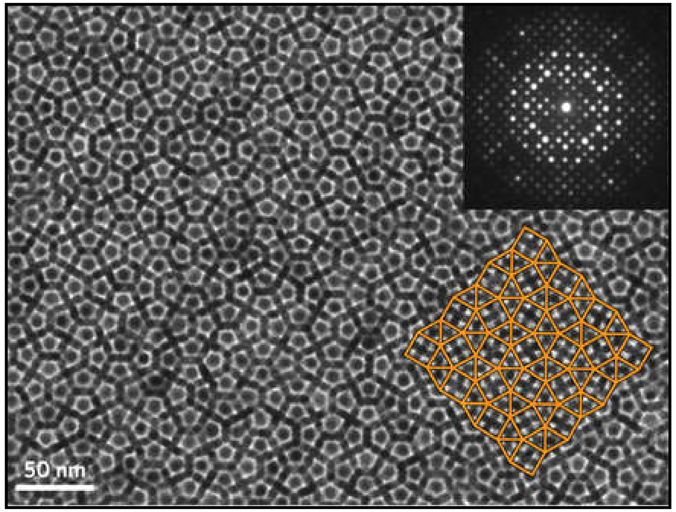


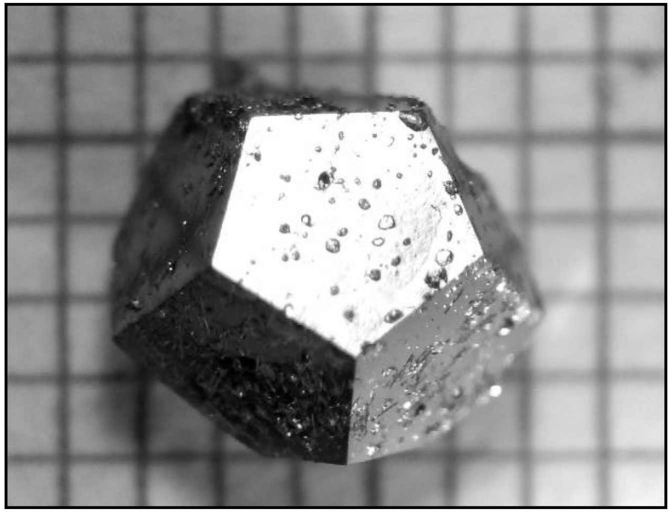
Quasi-Crystal

- Neither crystalline nor amorphous
  - 5, 8, 10, or 12-fold symmetry

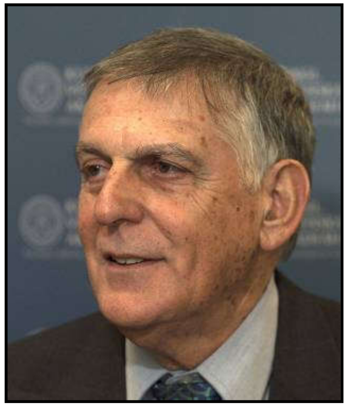


Penrose tiling





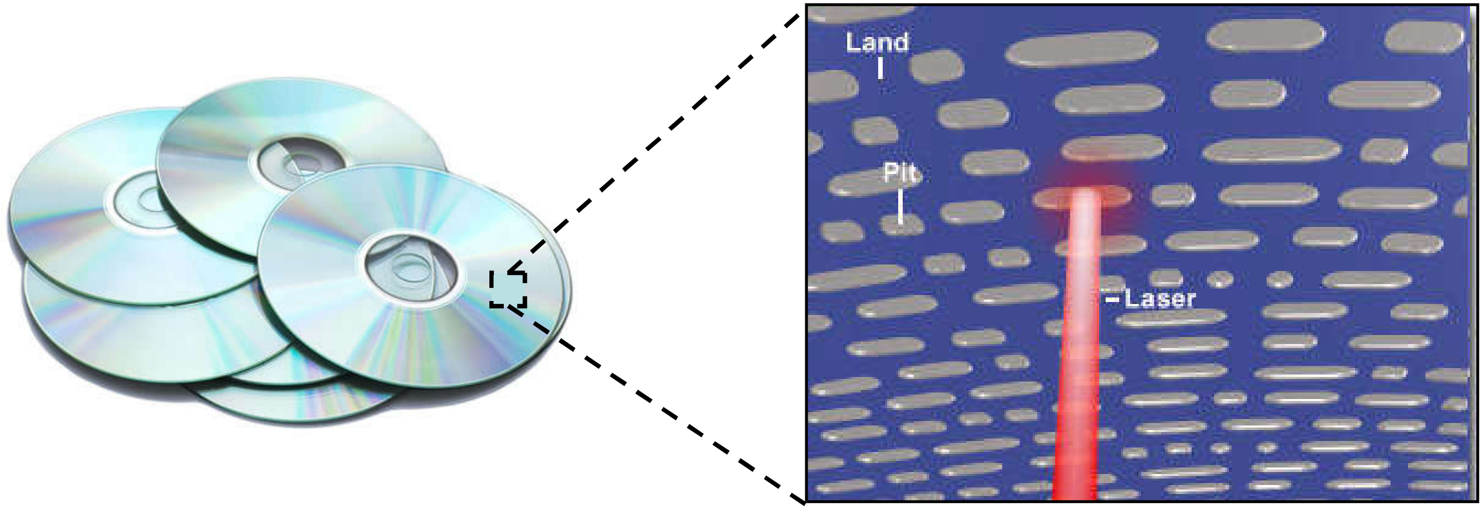
A Ho-Mg-Zn quasicrystal

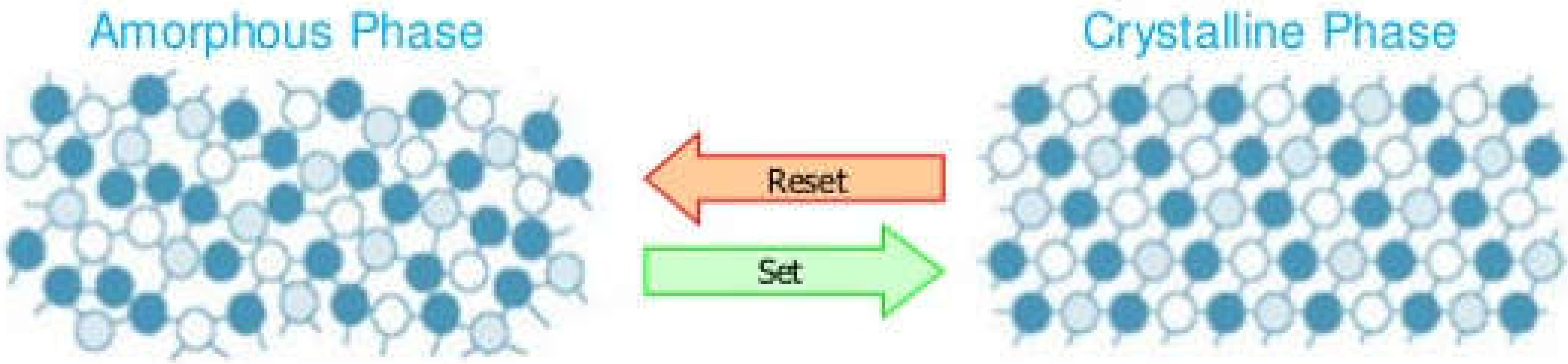


D. Shechtman
2011 Nobel Prize in Chemistry

Optical Disc

- **Phase Change Memory**



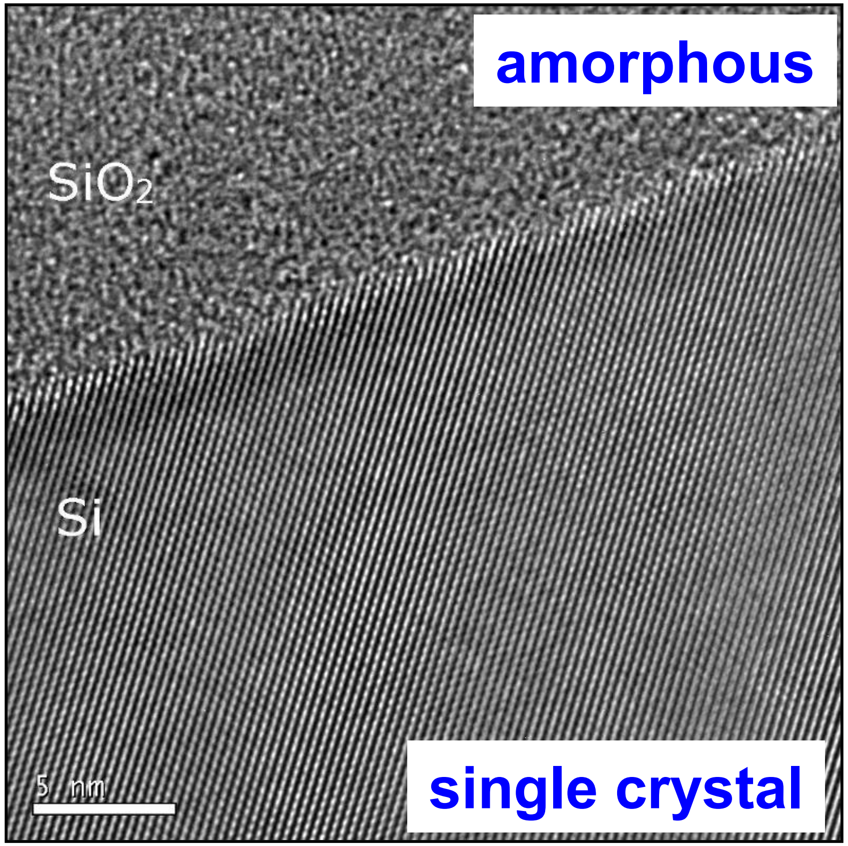


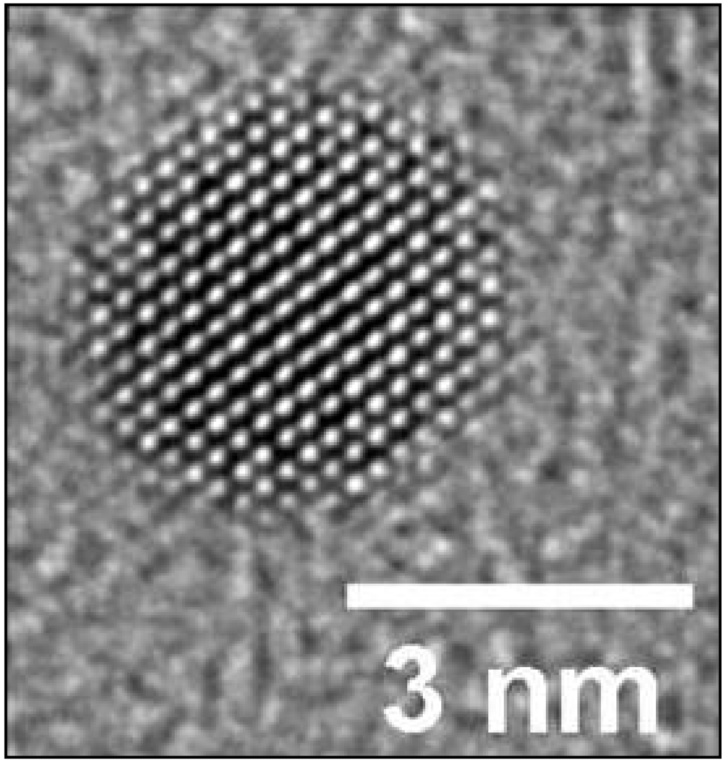
Materials Characterization

- **SEM / TEM**
  - Scanning / Transmission Electron Microscope
- **HRTEM**
  - High Resolution Transmission Electron Microscope
- **XRD**
  - X-ray Diffraction
- **DSC**
  - Differential Scanning Calorimetry

Materials Characterization

- **HRTEM**
  - **High Resolution Transmission Electron Microscope**



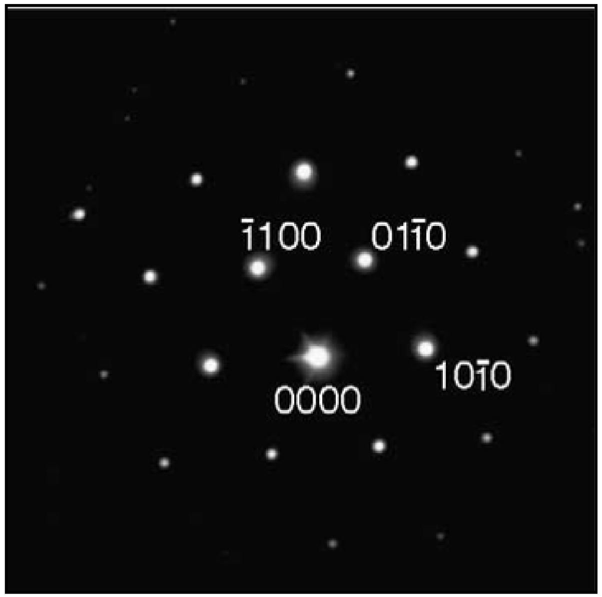


quantum dot

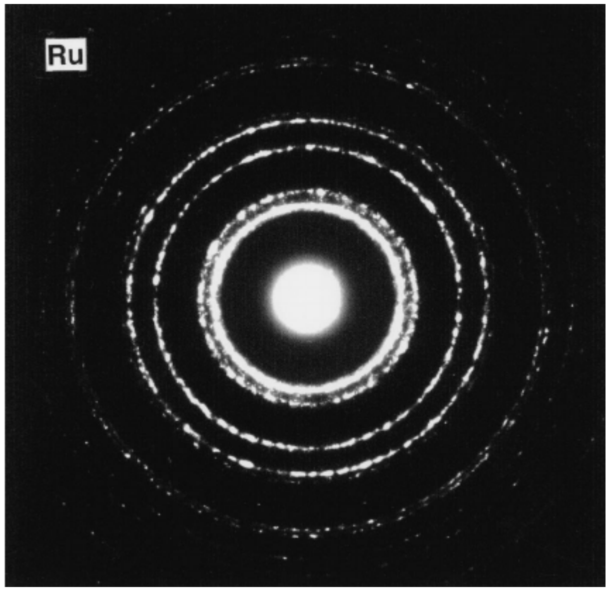
Materials Characterization

- **HRTEM**
  - **High Resolution Transmission Electron Microscope**

diffraction patterns



single crystal

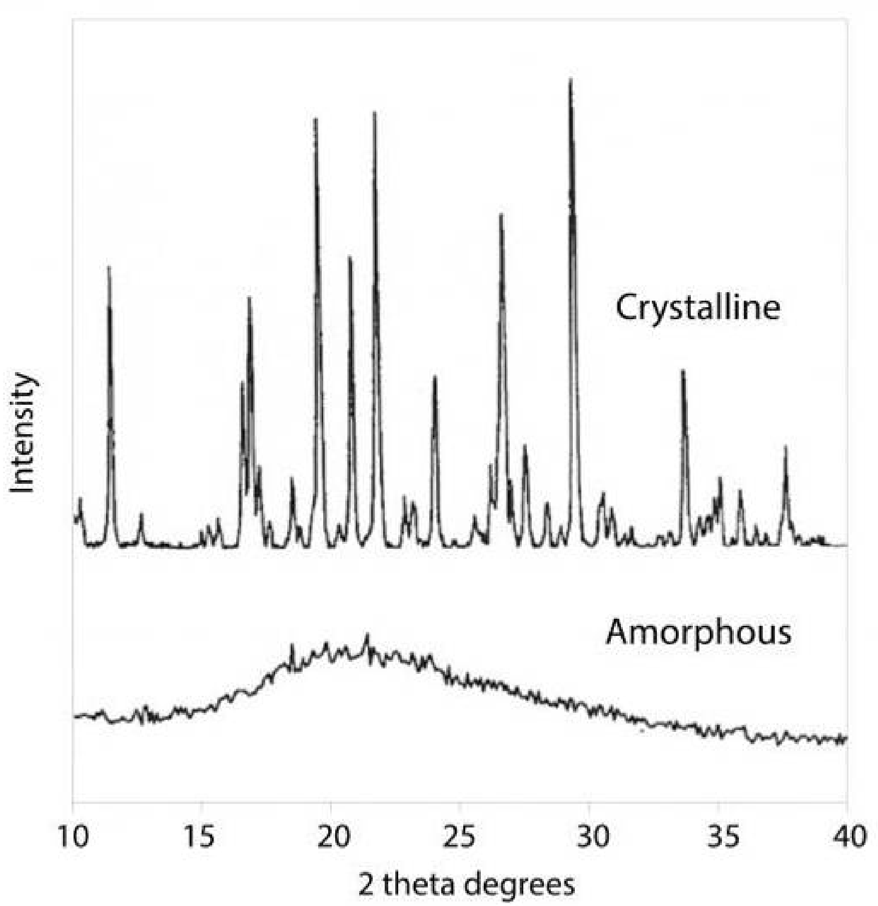


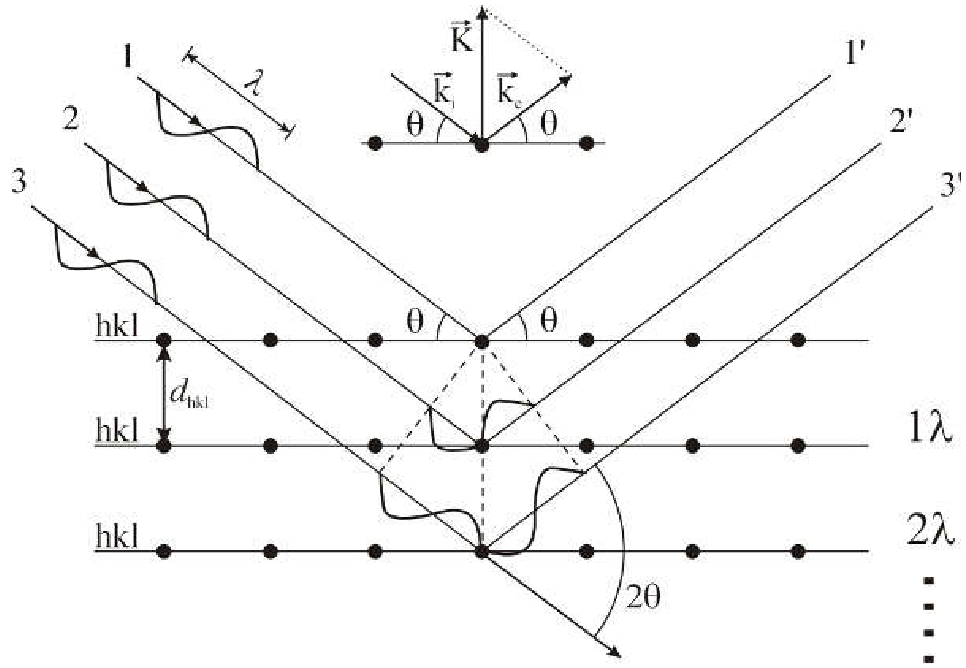
polycrystal

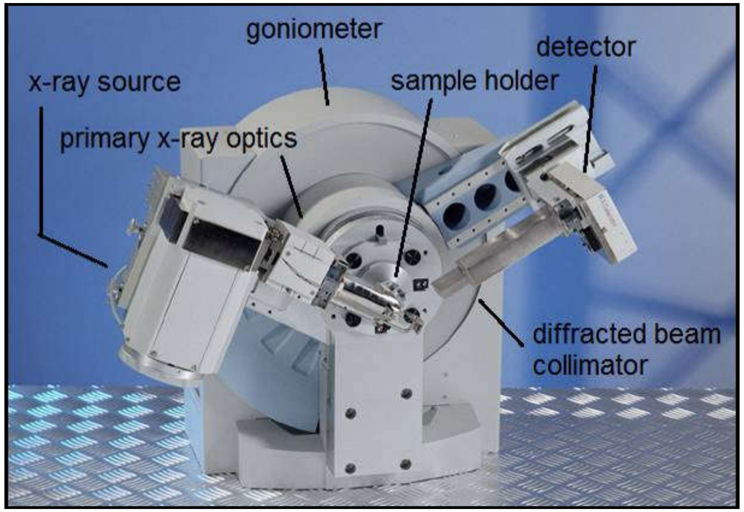
amorphous

Materials Characterization

- **XRD**
  - **X-ray Diffraction**

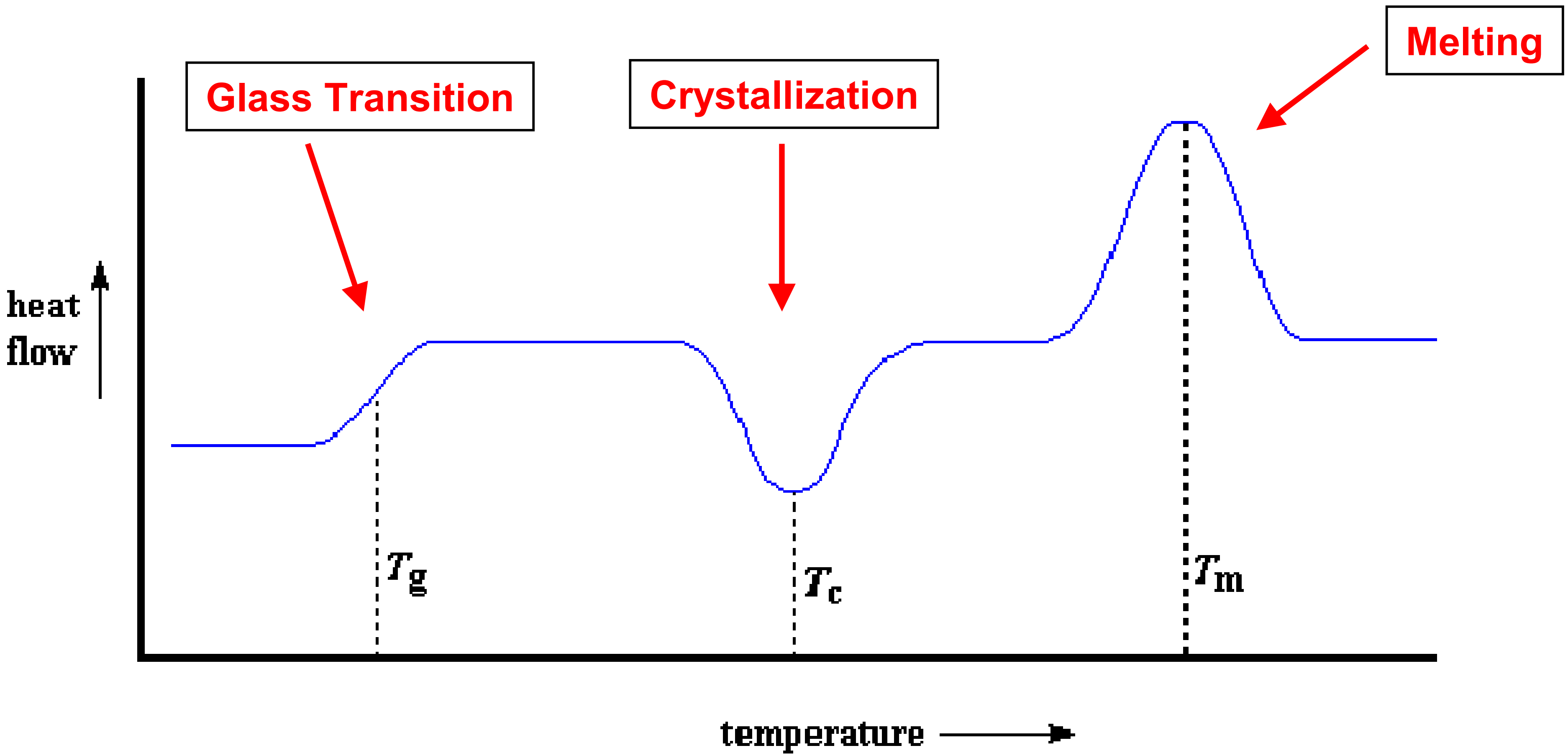






Materials Characterization

- **DSC**
  - Differential Scanning Calorimetry

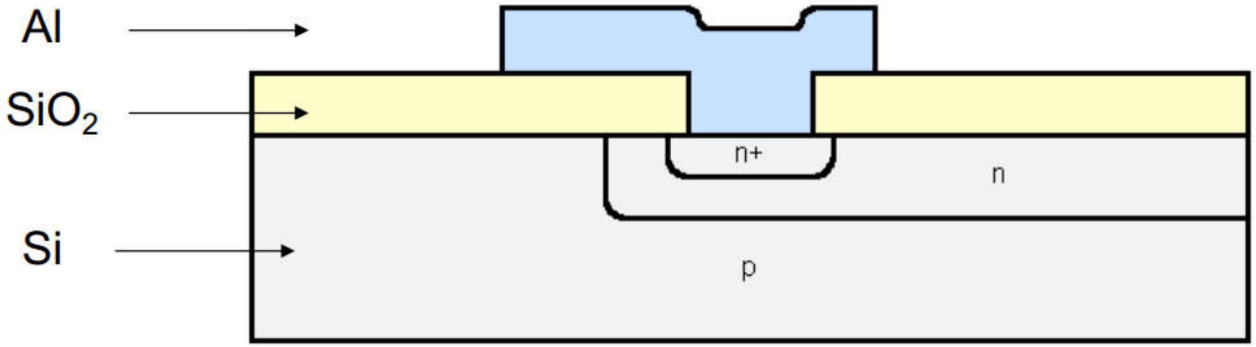


CMOS Device

polycrystalline →

amorphous →

single crystalline →



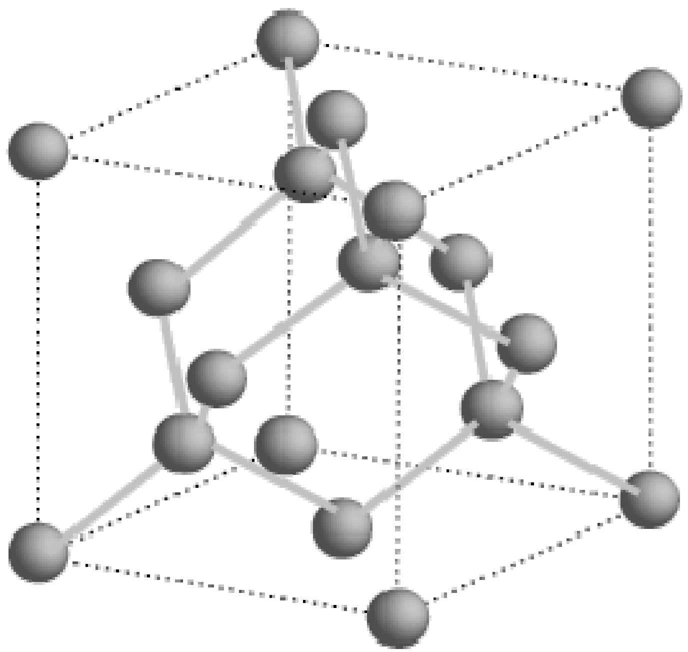
Silicon

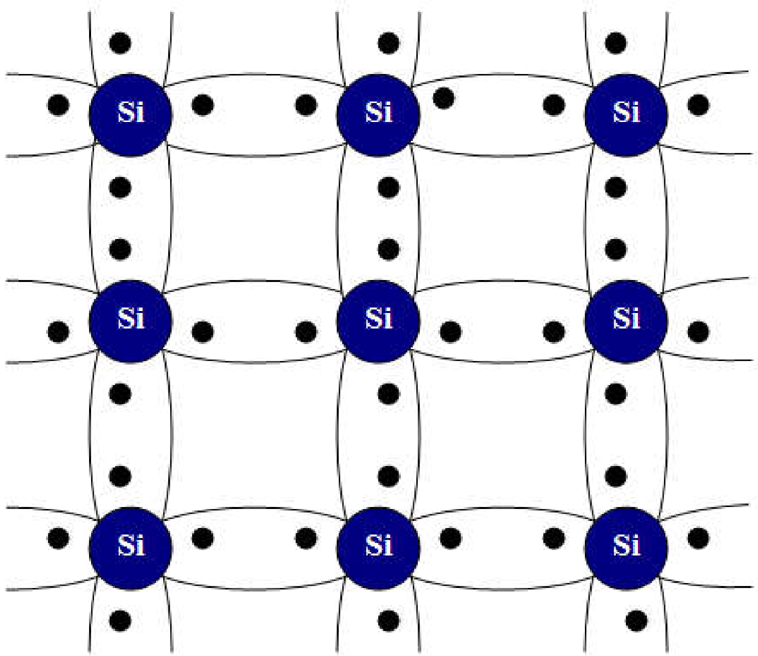
SiO_2

Metal

Substrates for Devices

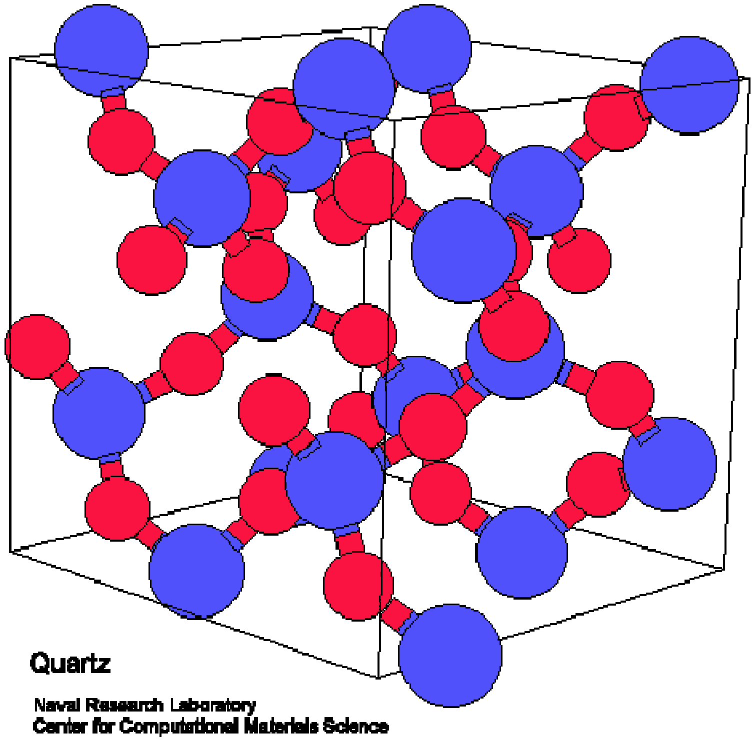
- **Usually single crystals**



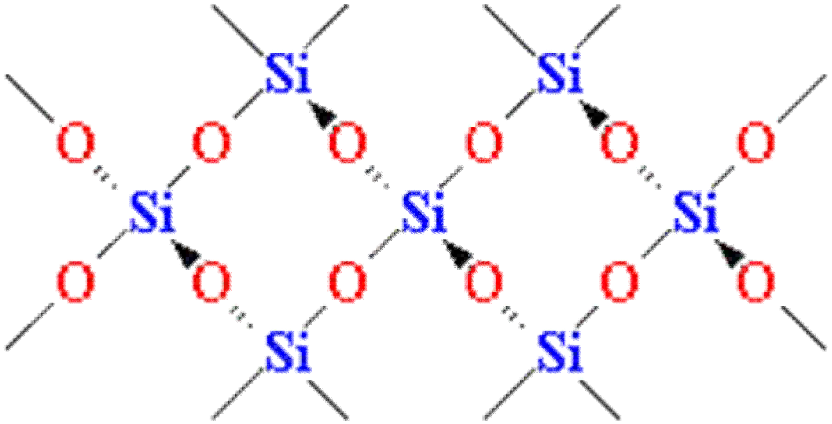


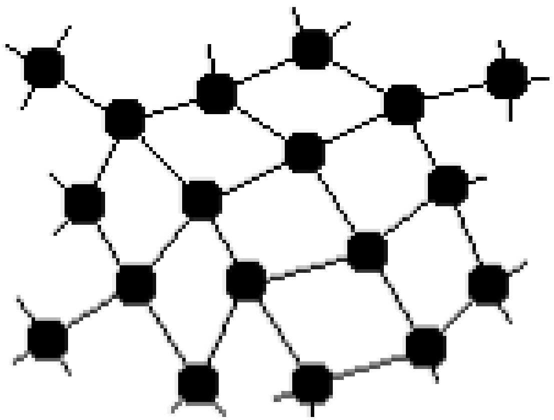
diamond structure:
Si, Ge, C, ...

Substrates for Devices



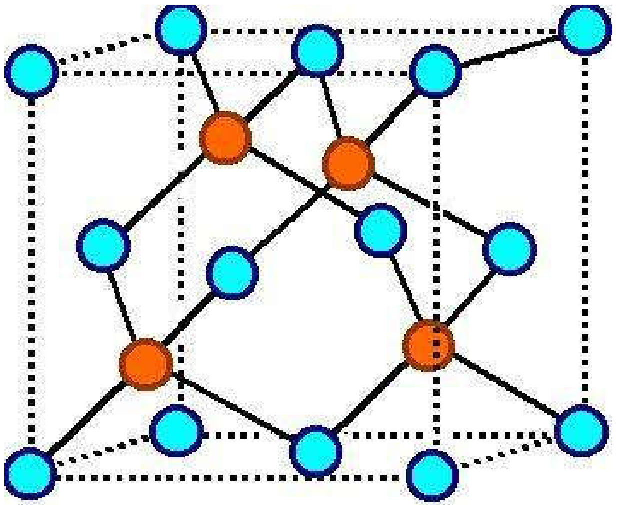
quartz (SiO_2)
single crystalline



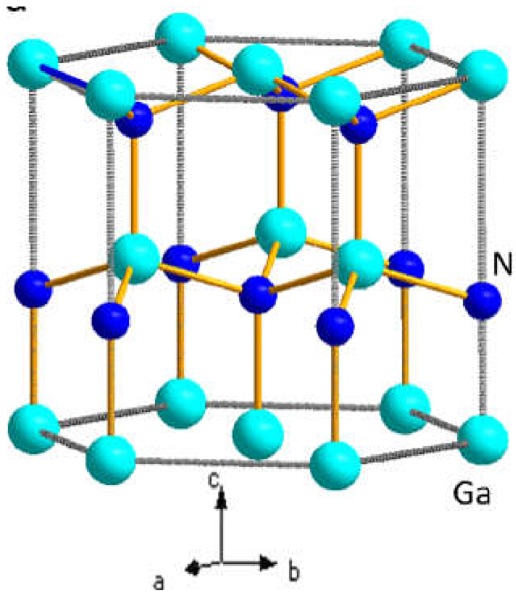


amorphous
glass

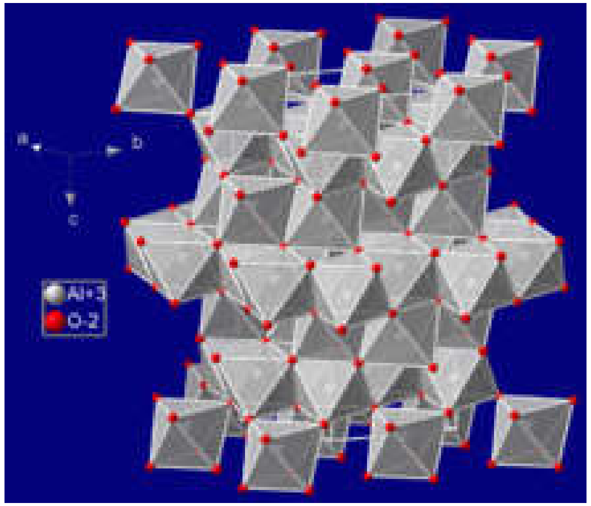
Substrates for Devices



zinc blende structure:
GaAs, InP, β-SiC, ...

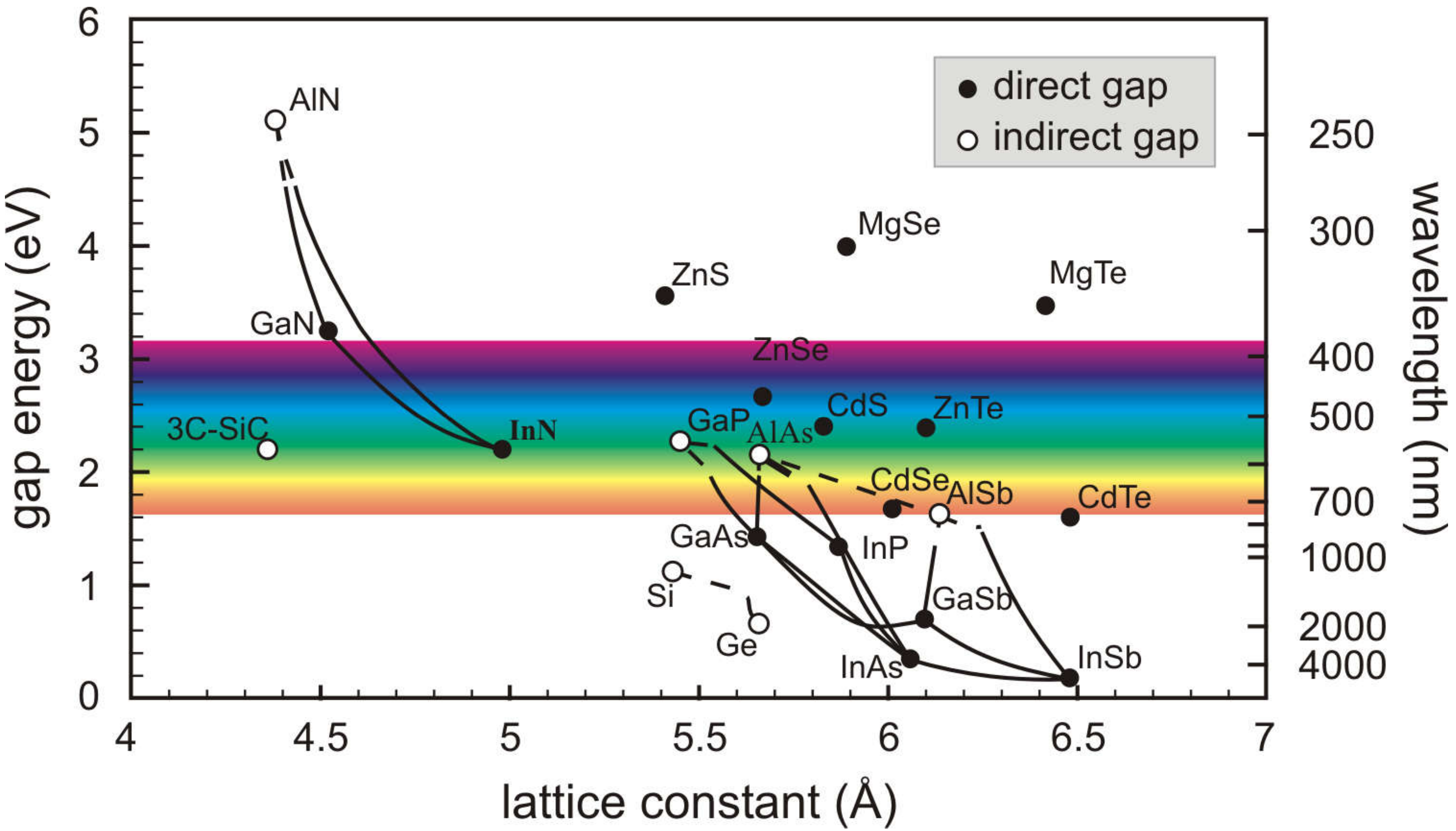


Wurtzite structure:
α-SiC, GaN, ZnO, ...



sapphire (Al_2O_3)

Lattice Constants vs. Bandgap



Requirement for Electronics

- low cost
- single crystal
- p-doping and n-doping
- low defect level
  - purity > 99.99999....%
  - dislocation < 1000 /cm^2
- suitable bandgap
  - too large -> high voltage, power, ...
  - too small -> thermal noise, leakage, defects, ...
- semiconductor/oxide interface quality
- mobility, surface uniformity, ...

Silicon vs. Germanium

Silicon

- earth abundant
  - > 25% on earth
- perfect Si/SiO_2 interface
- bandgap 1.1 eV

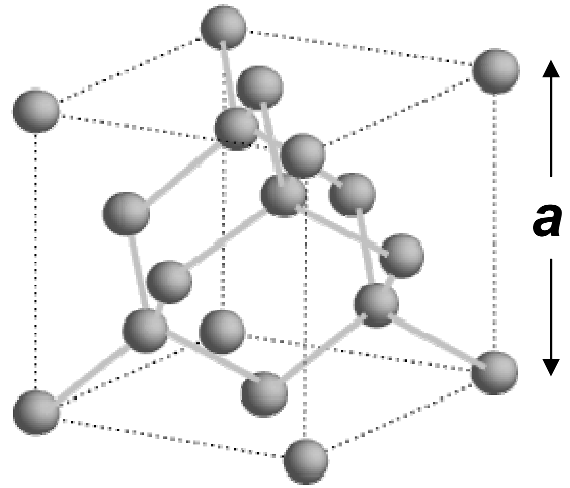
vs.

Germanium

- expensive
- GeO_2 is not stable
- bandgap 0.67 eV

Silicon wins
and will always win (?)

Properties of Silicon



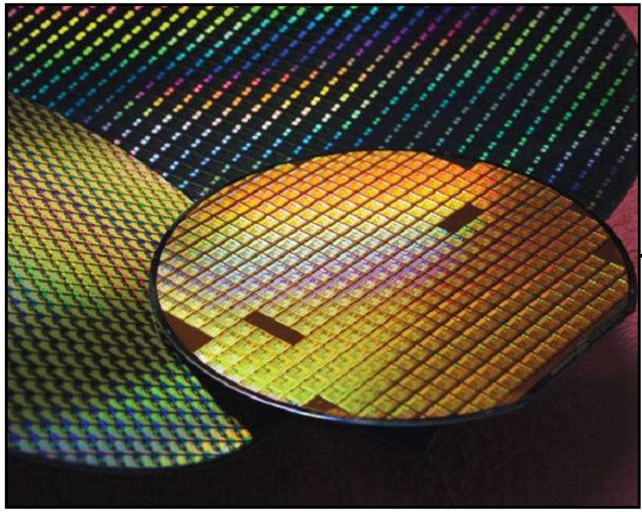
- **Structural**
  - diamond structure (FCC)
  - lattice constant a = 5.431 Å
  - atomic density = 5 * 10^{22} /cm^3
  - melting point = 1417 ^oC
- **Electronic**
  - bandgap E_g = 1.12 eV
  - dielectric constant ε_r = 11.9
  - mobility: electron μ_e = 1500 cm^2/V/s, hole μ_h = 450 cm^2/V/s
  - intrinsic carrier density n_i = 1.45 * 10^{10} /cm^3
- **Optical**
  - refractive index n = 3.6
  - absorbs < 1100 nm, transparent > 1100 nm

How to Make Silicon Wafers?

Video

SiO_2

raw Si



IC chips

Si ingots and wafers

How to Make Silicon Wafers?

SiO_2

raw Si

$$SiO_2 + 2C = Si + 2CO$$ at 2000 °C

Metallurgical Grade Silicon, purity ~ 98%
Applications: aluminum, silicone, ...

How to Make Silicon Wafers?

SiO_2

raw Si

$$Si + 4HCl = SiCl_4 + 2H_2$$
$$SiCl_4 + 2H_2 = Si + 4HCl$$

purification (Siemens process)

Polycrystalline Silicon, purity > 99.99%
Applications: solar cells, ...

How to Make Silicon Wafers?

poly crystal -> single crystal

Czochralski process (CZ)

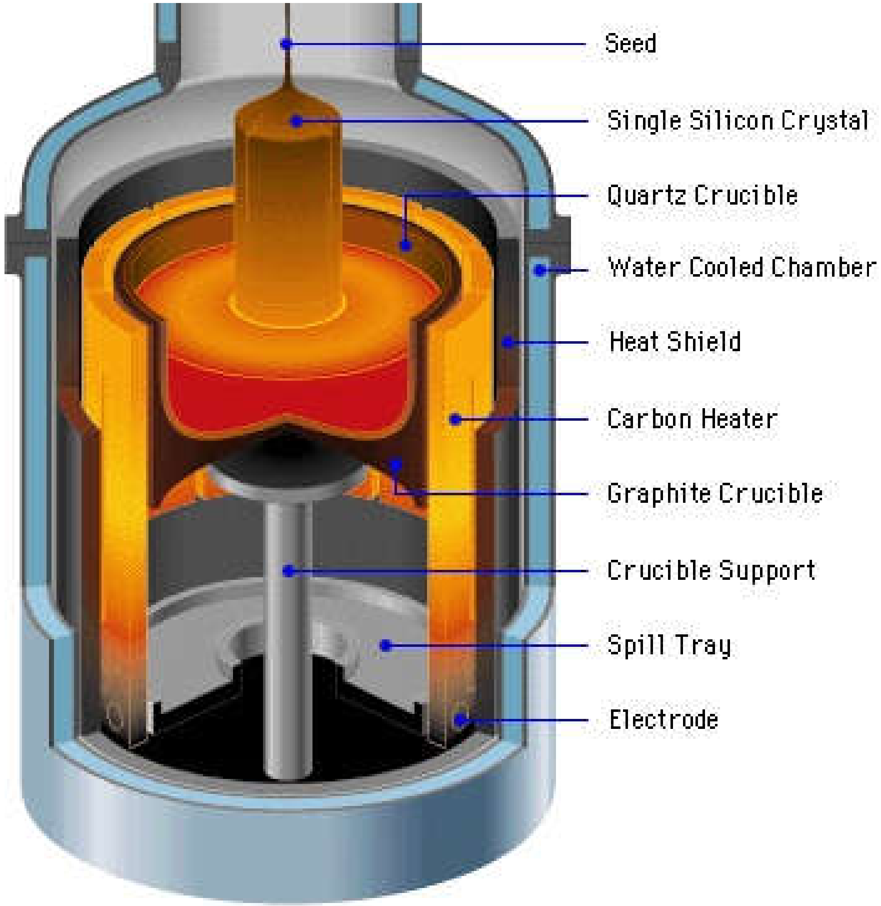
Float-zone process (FZ)

raw Si

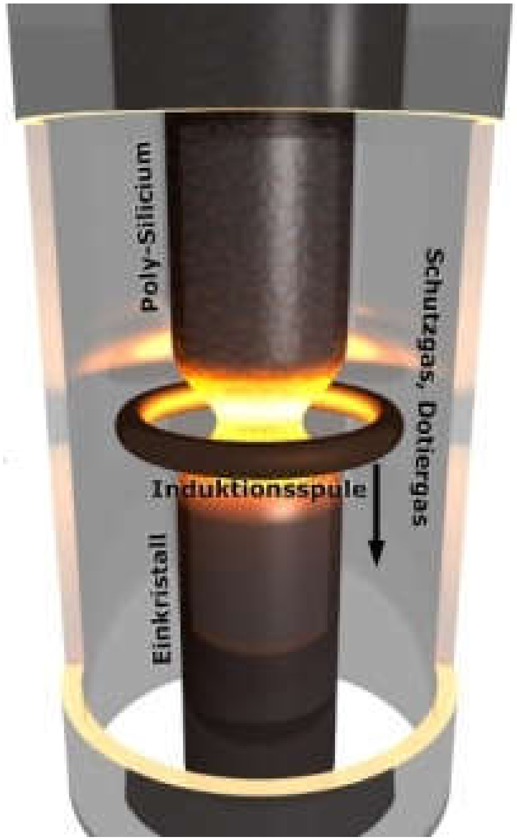
Si ingots and wafers

How to Make Silicon Wafers?

Czochralski process (CZ)

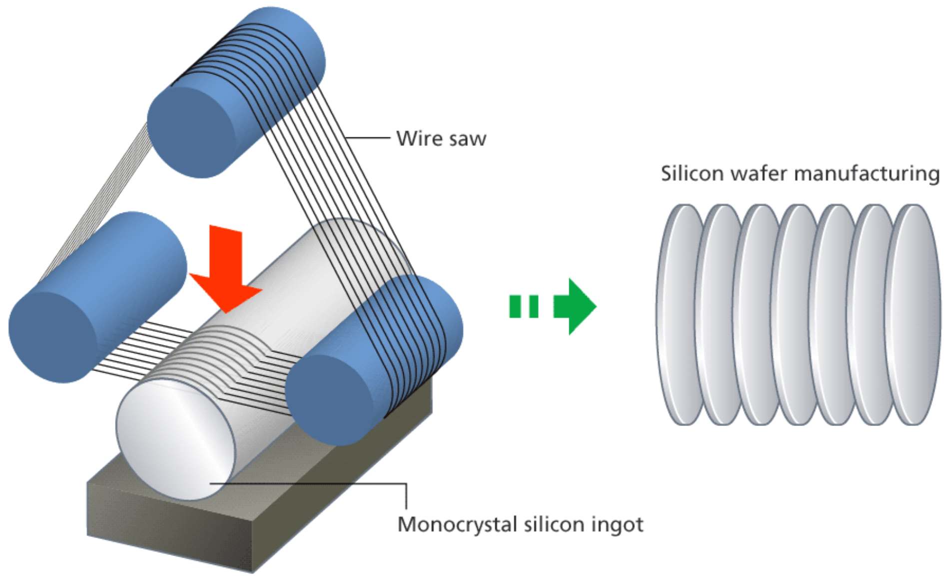


Float-zone process (FZ)

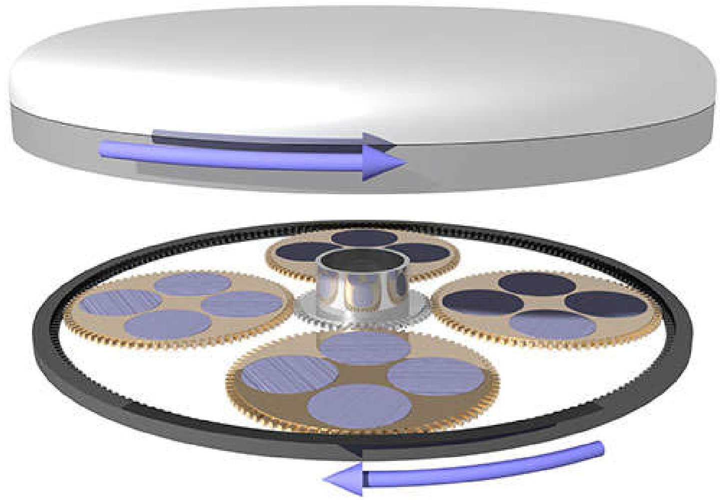


How to Make Silicon Wafers?

wafer slicing

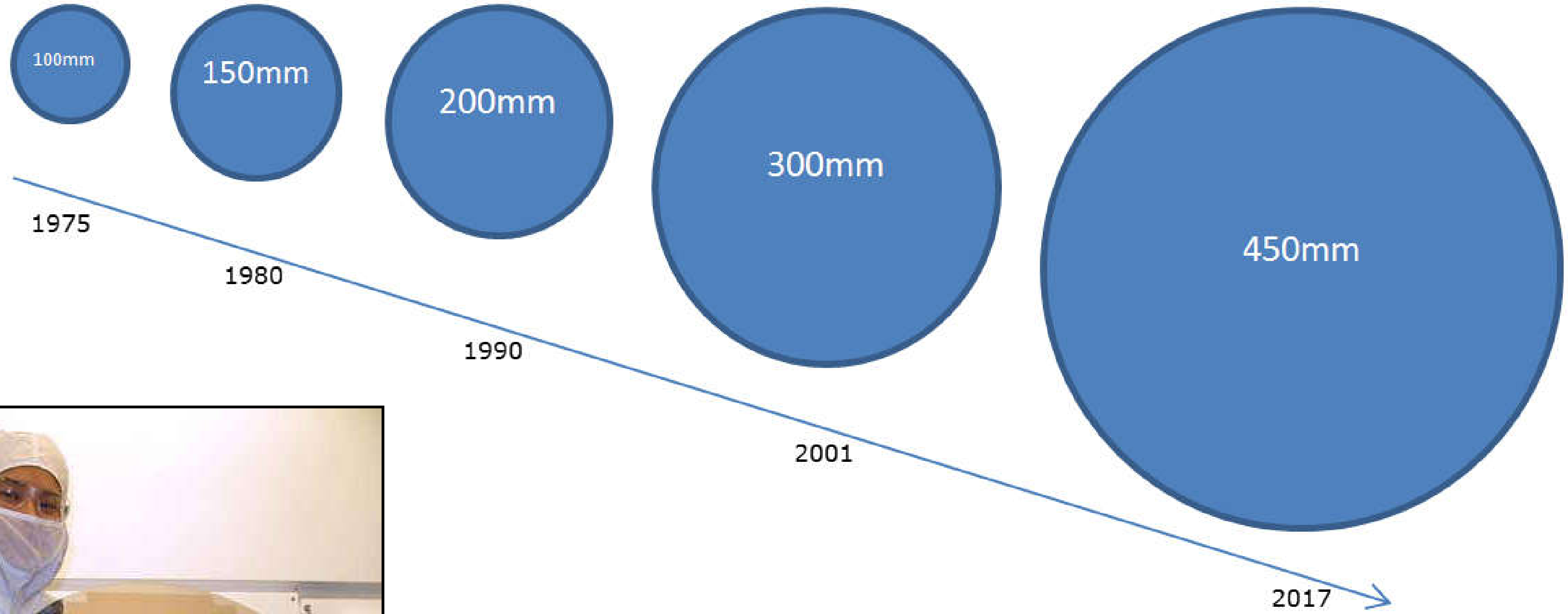


wafer polishing



Silicon wafers: size

4 inch 6 inch 8 inch 12 inch 18 inch



18 inch wafer

Silicon wafers: purity

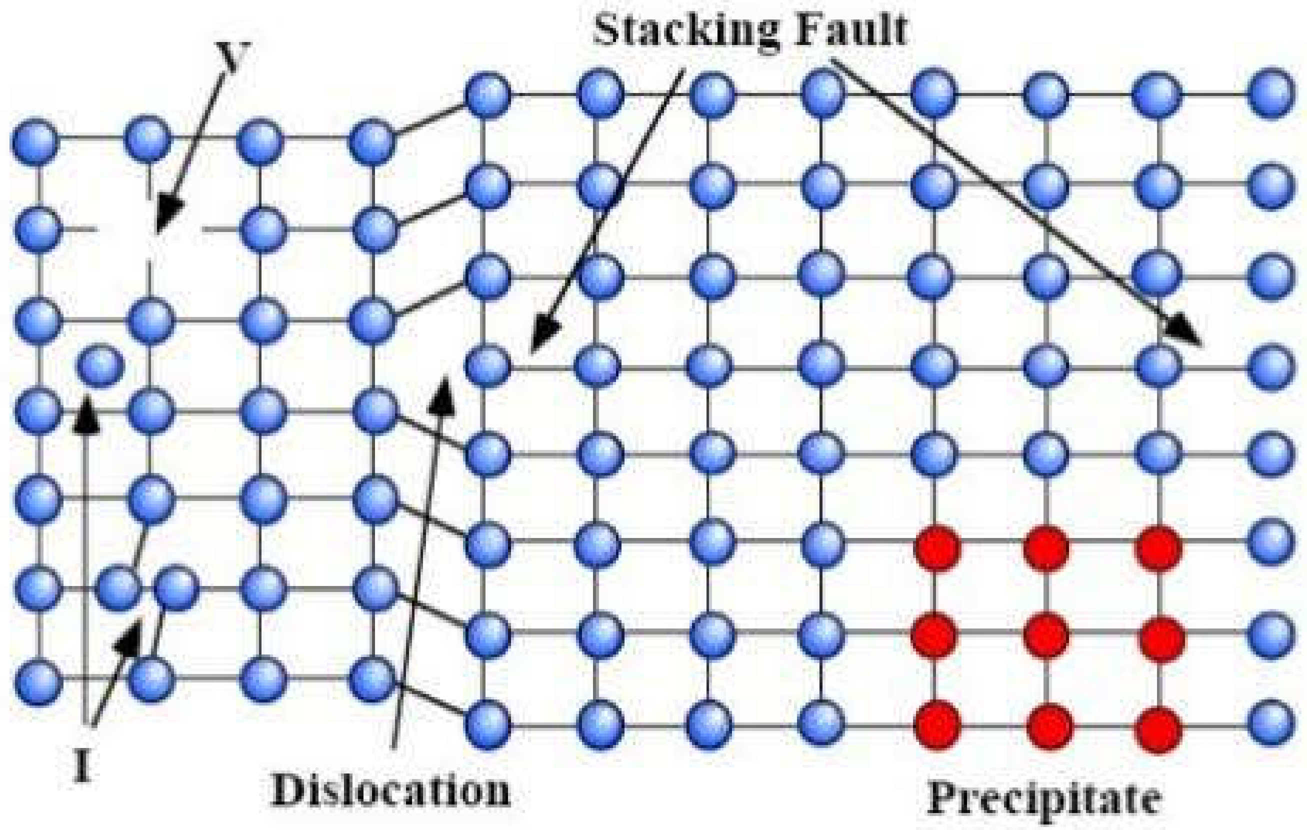
- **Metallurgical grade**
  - polycrystalline
  - purity > 98%
  - application: aluminum alloy, silicone

- **Solar grade**
  - polycrystalline
  - purity > 99.99% (4N)
  - application: solar cells

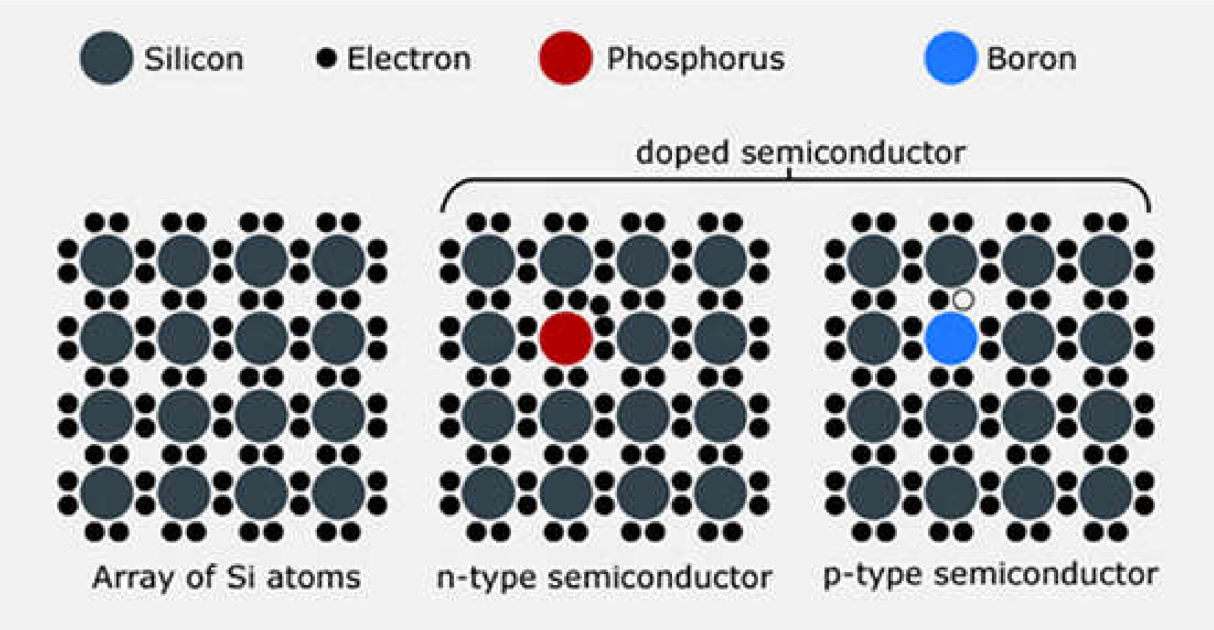
- **Electronic grade**
  - single crystalline
  - purity > 99.9999999% (9N)
  - application: IC industry, high efficiency solar cells

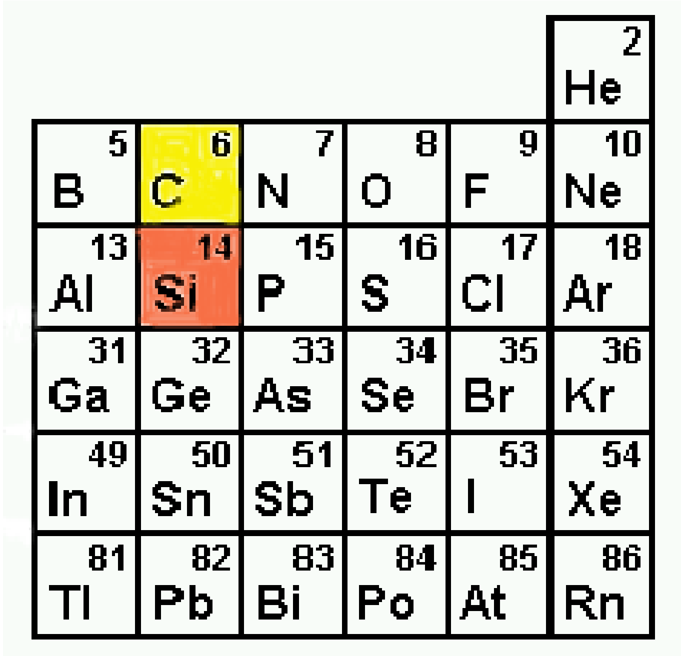
Silicon wafers: defects

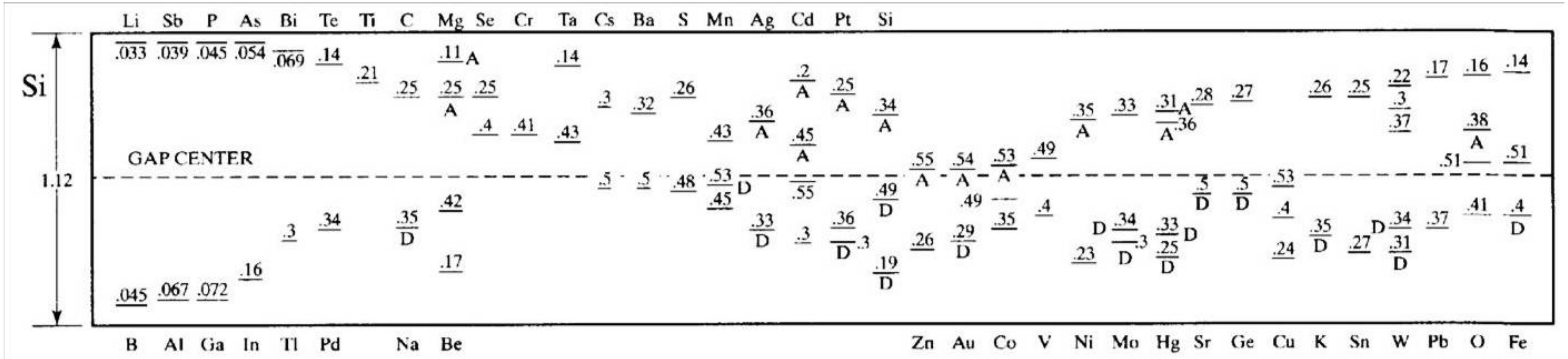
- Point Defects e.g. Vacancies (V), Interstitials (I)
- Line Defects e.g. Dislocations
- Area Defects e.g. Stacking Faults ("extrinsic" or "intrinsic" form along {111} planes)
- Volume Defects e.g. Precipitates, Collection of Vacancies



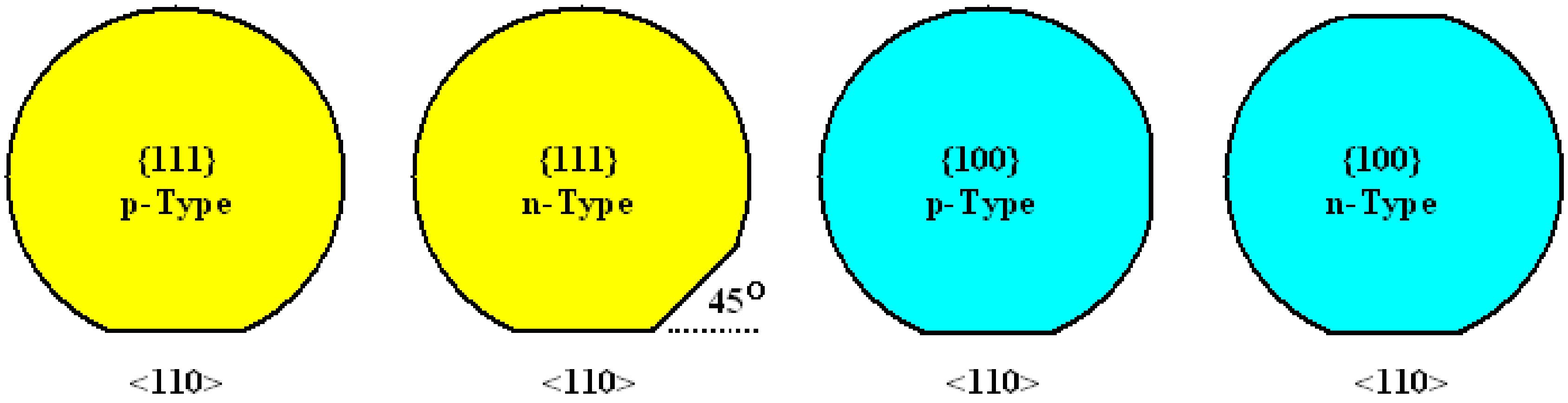
Silicon wafers: doping



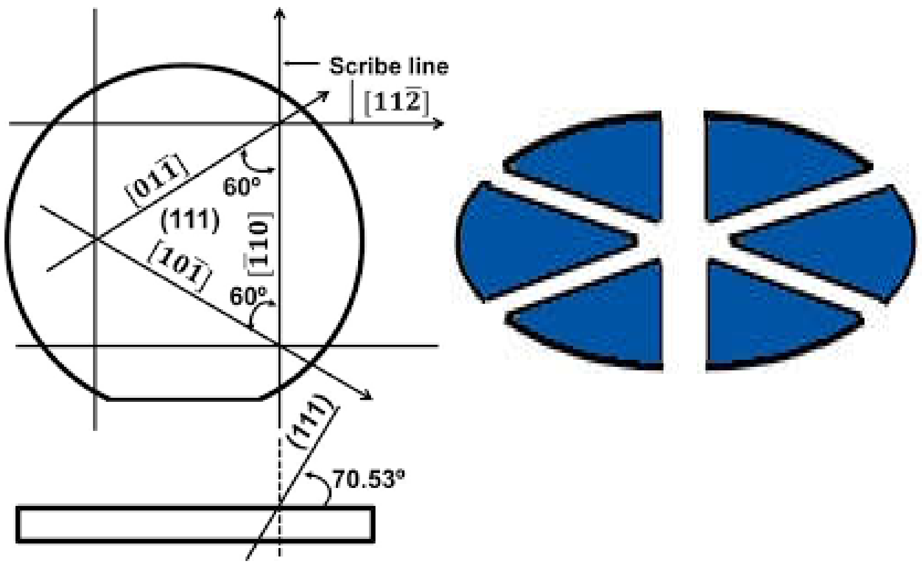


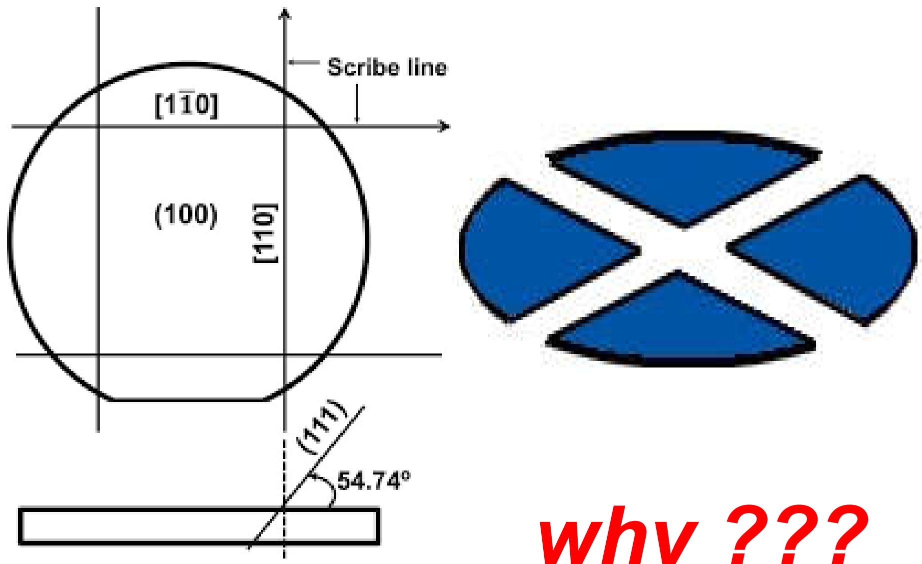


Silicon wafers: orientation



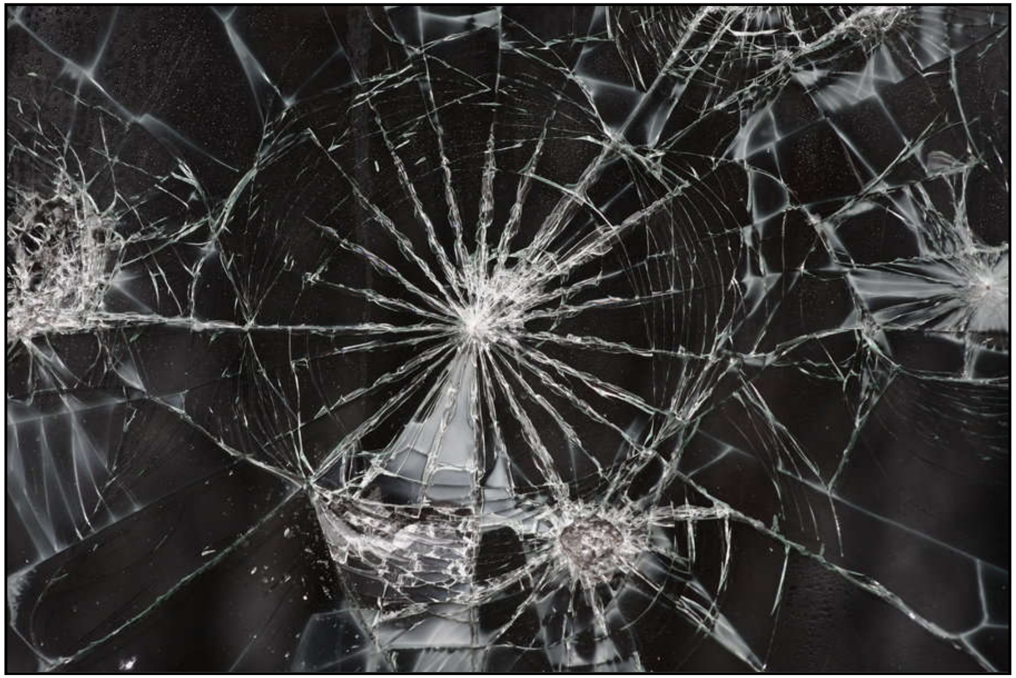
cleavage direction

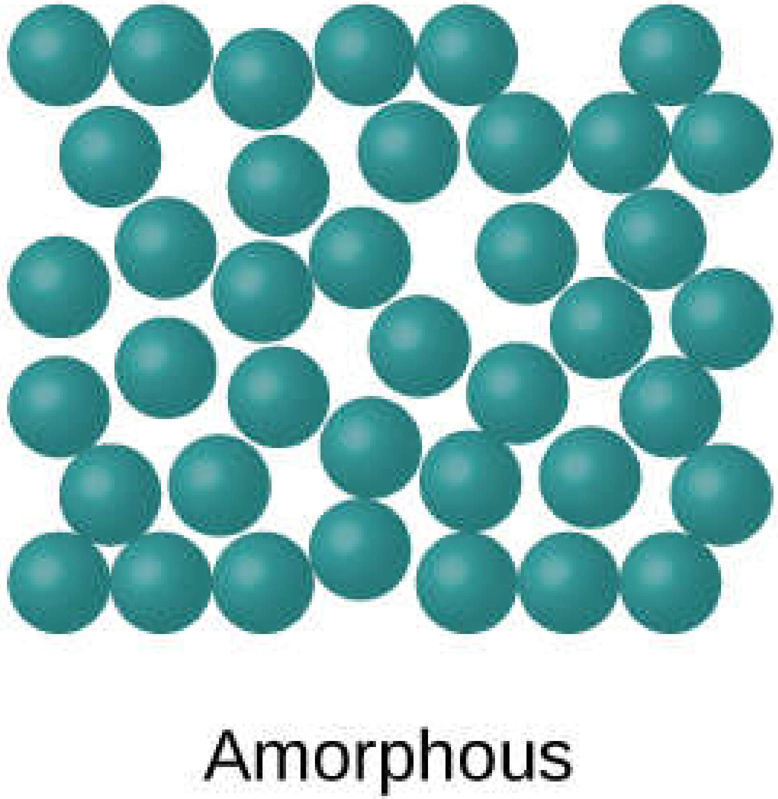




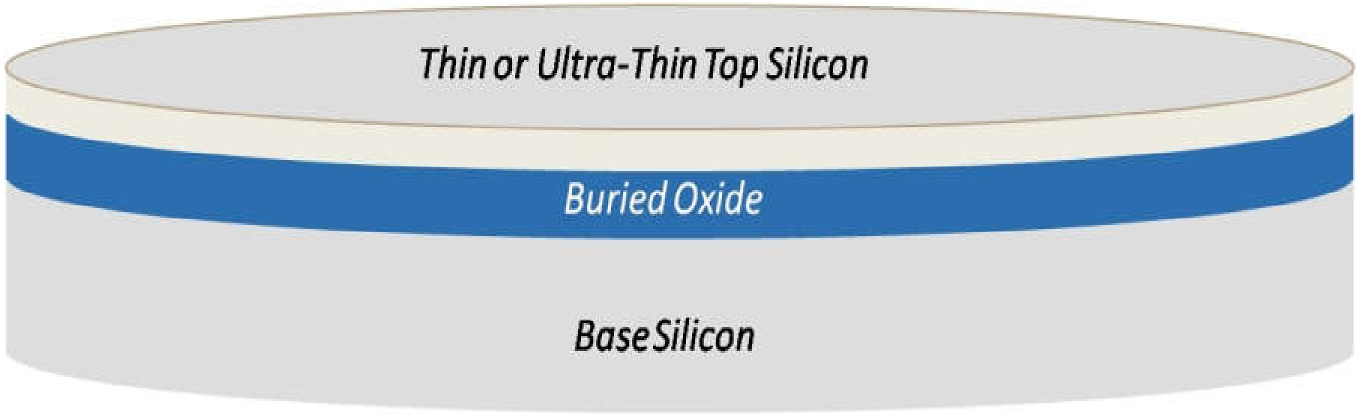
why ???

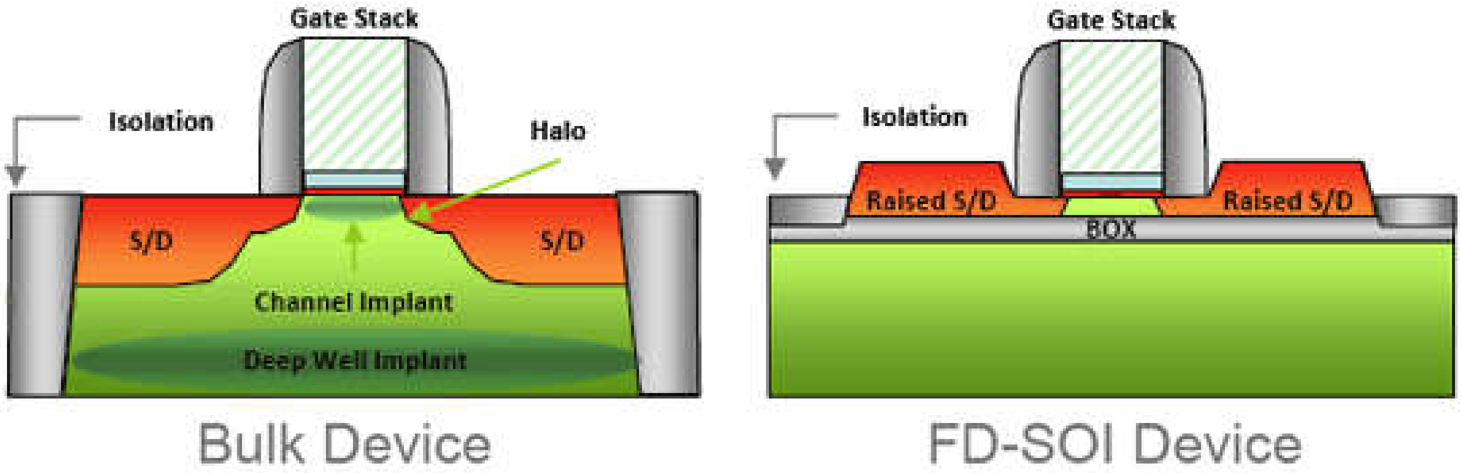
Breaking Amorphous Materials



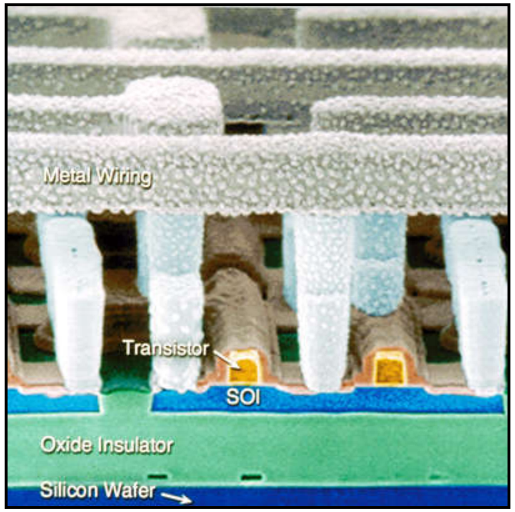


Silicon-on-Insulator (SOI)

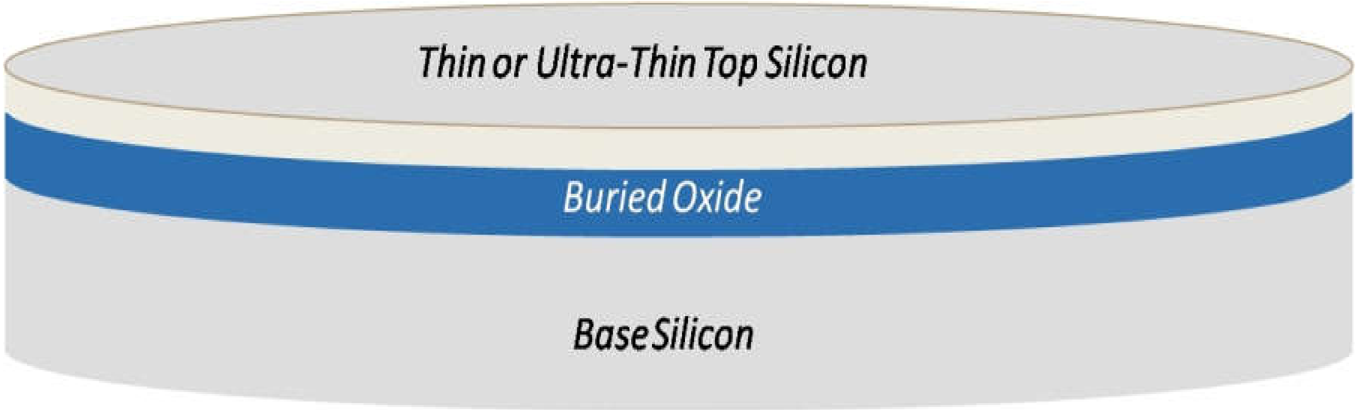


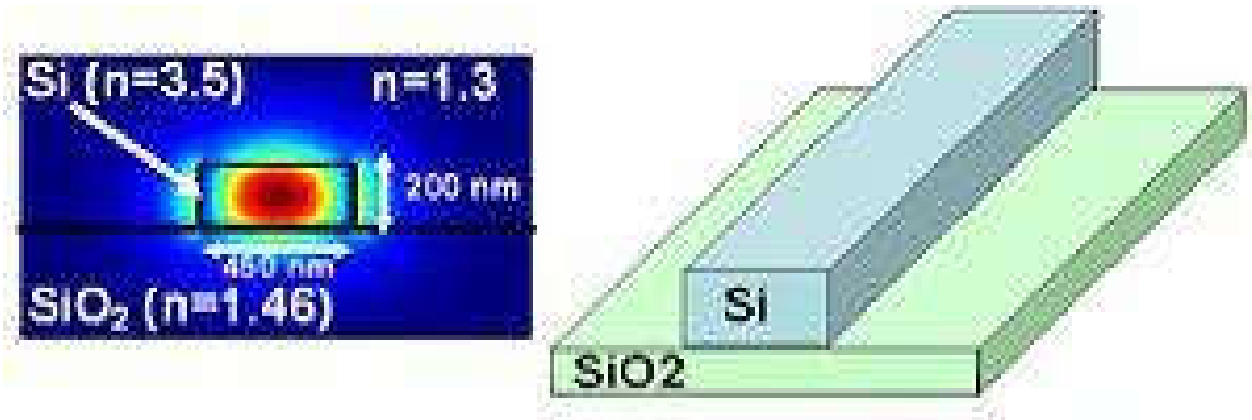


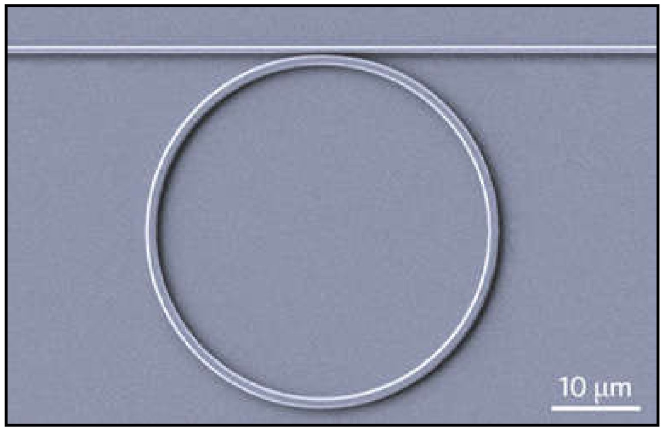
The fully depleted SOI transistor at 20 nm is significantly simpler than even a simplified version of the bulk CMOS transistor.



Silicon-on-Insulator (SOI)







Silicon waveguide

Ring resonator

Other single crystals

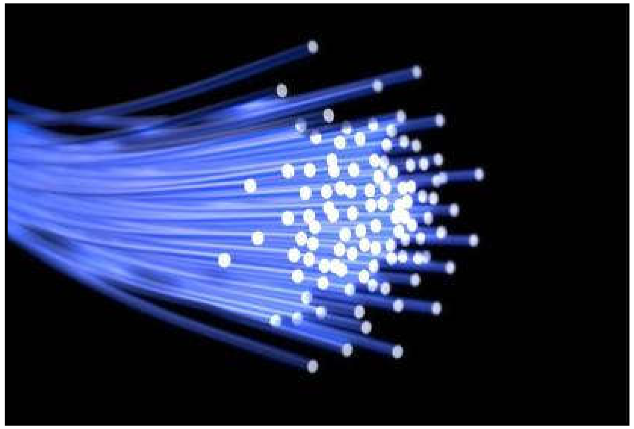
Ge

GaAs

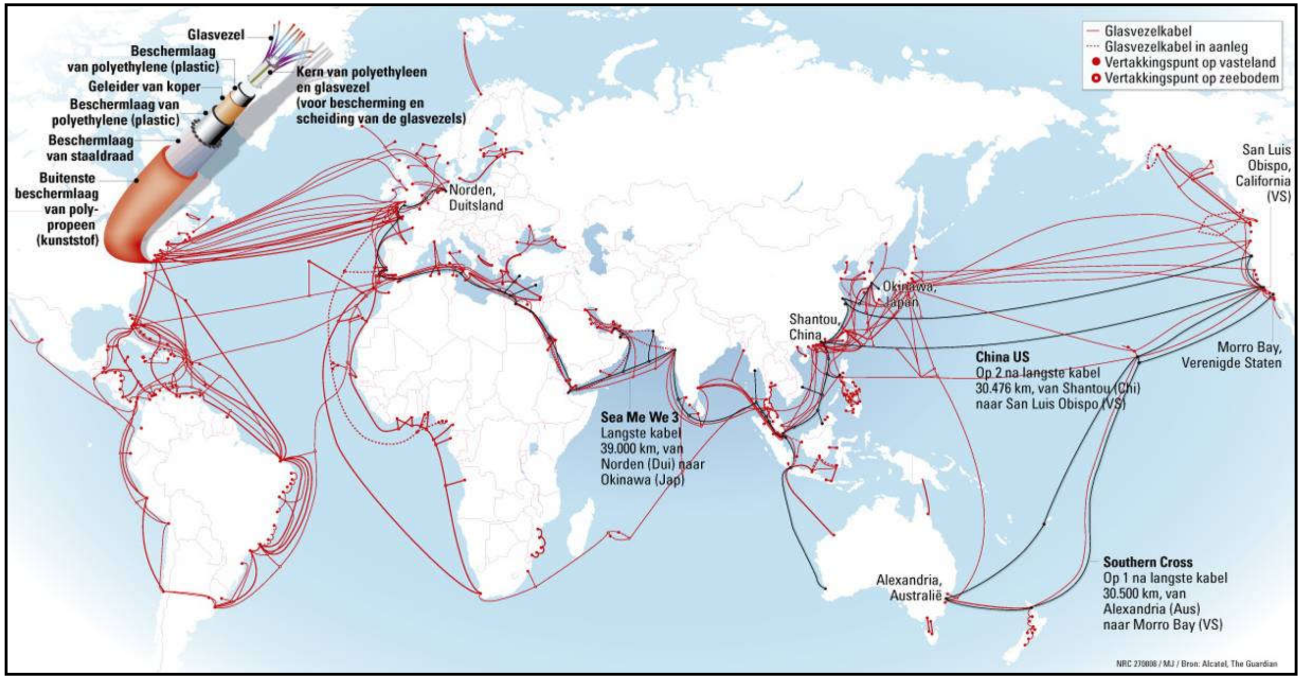
sapphire

Q: Can we make diamond crystals?

Optical Fibers



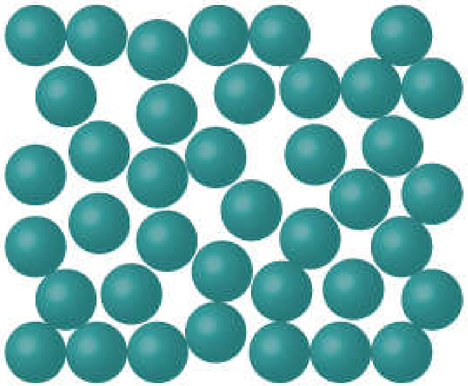
silica (SiO_2)



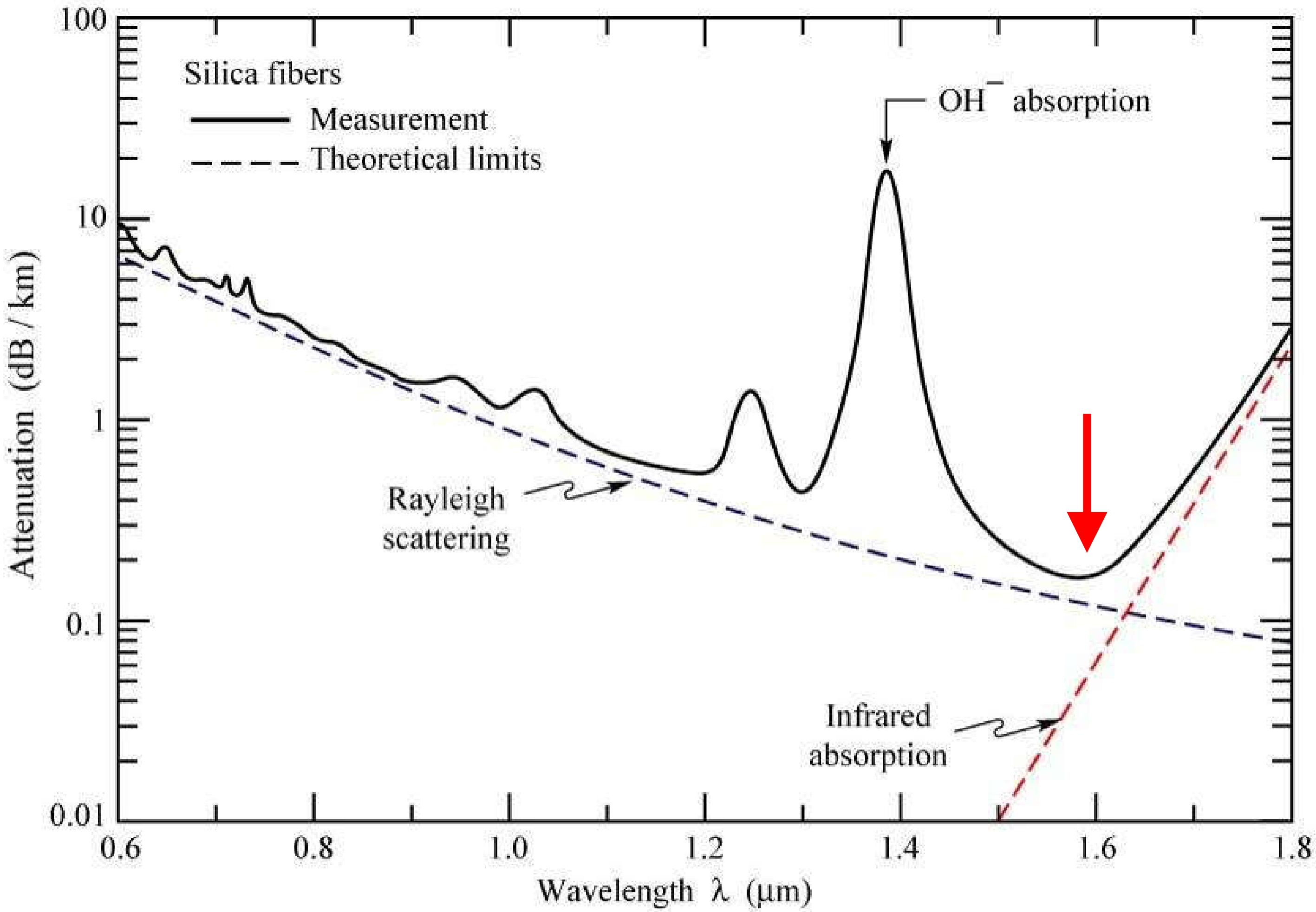
K. Kao (高锟) (1933–2018)
2009 Nobel Prize in Physics

K. C. Kao, G. A. Hockham, *Proc. IEE* **113,** 1151 (1966)

Absorption of Silica (SiO_2)



Amorphous



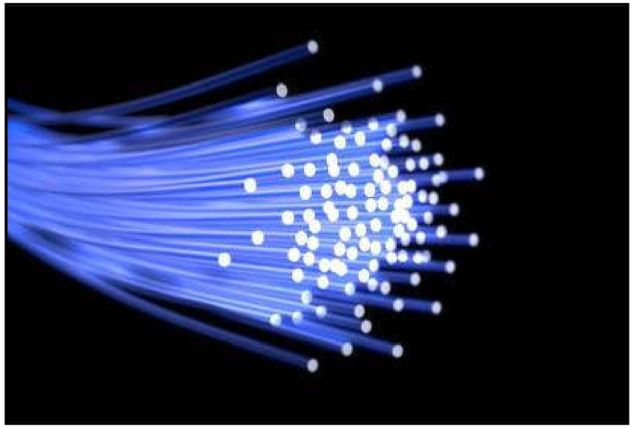
minimum loss at 1550 nm, 0.2 dB/km

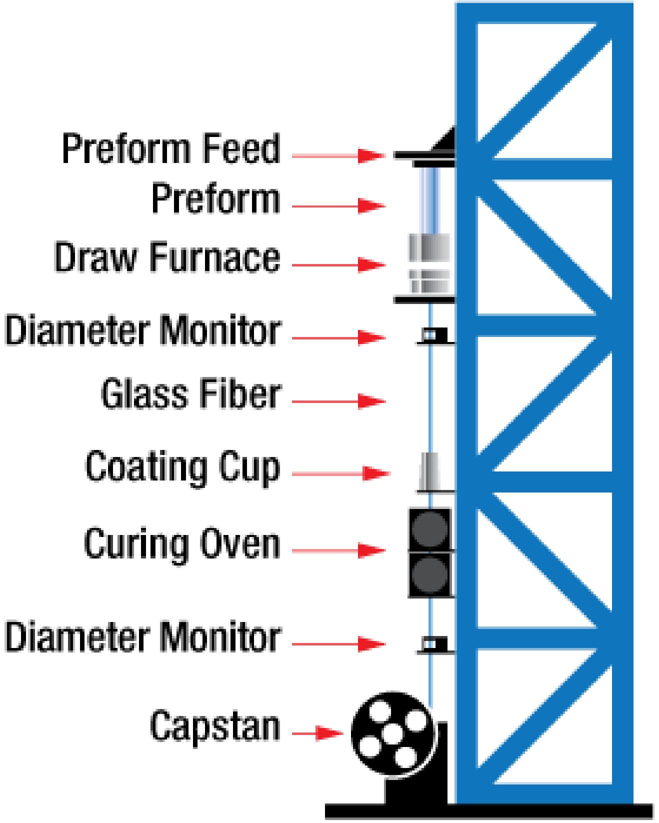
~ 2% loss every kilometer

Optical Fiber Drawing

preform

fibers

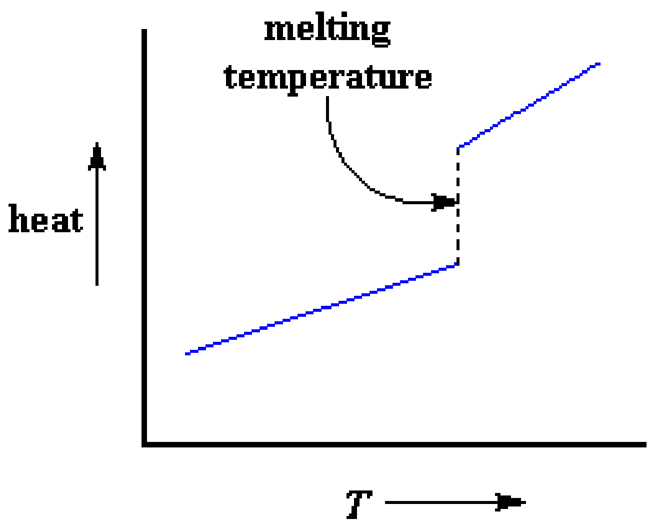




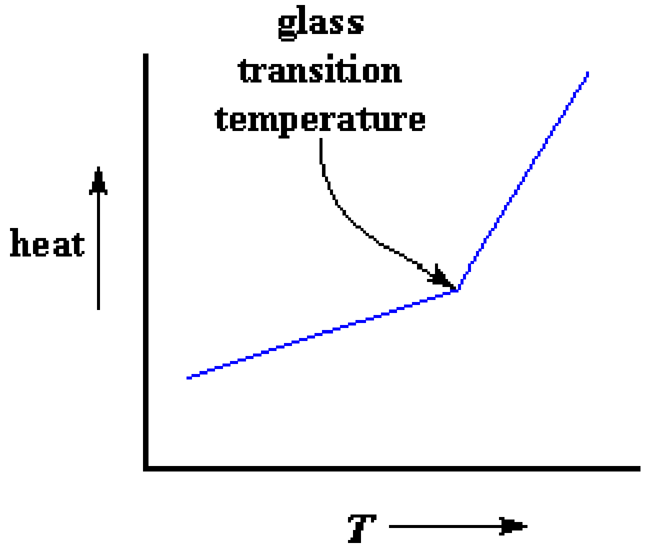
Video

Glass Transition

吹玻璃



1st order tansistion



2nd order tansistion

glassy / plastic state

viscous / rubbery state

Optical Fibers